J.K. Cable

# Evaluation of Maturity and Pulse Velocity Measurements for PCC Traffic Opening Decisions

March, 1998

Sponsored by the
Project Development Division of the
Iowa Department of Transportation and the
Iowa Highway Research Board

Iowa DOT Project HR-380

Iowa Department of Transportation

**Final**

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Department of Civil and Construction Engineering

Dr. James K. Cable P.E.

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## DISCLAIMER

"The opinions, findings, and conclusions expressed in this publication are those of the author and not necessarily those of the Iowa Department of Transportation."

## ACKNOWLEDGEMENTS

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A special thanks goes to Jim Reinsche for his work in the collection of data for this project. Without his dedication and knowledge of concrete the project would not have been a success. This daily data collection effort was aided by Jennifer Ries and Shane Tymcowicz of the Iowa DOT. Without Shanna Duggan, Trevor Brown, Greg Mulder, and Lisa McDaniel much of the data analysis would not have been completed. They not only assisted in the work, but had the chance to learn much about the research work and concrete pavement construction. This project was truly a partnership between the research team and members of the Office of Materials; Iowa DOT in Ames, the Southeast Iowa Transportation Center office and the Mount Pleasant Construction Residency.

This type of project would not be possible without the cooperation of the Fred Carlson Co. and Superintendent Charlie Davis. This is another example of how Iowa and the construction industry benefits from cooperative research efforts.

**ABSTRACT**

Concrete paving is often at a disadvantage in terms of pavement type selection due to the time of curing required prior to opening the pavement to traffic. The State of Iowa has been able to reduce traffic delay constraints through material selection and construction methods to date. Methods for monitoring concrete strength gain and quality have not changed since the first concrete pavements were constructed in Iowa. In 1995, Lee County and the Iowa DOT cooperated in a research project, HR-380, to construct a 7.1 mile (11.43 km) project to evaluate the use of maturity and pulse velocity nondestructive testing (NDT) methods in the estimation of concrete strength gain.

The research identified the pros and cons of each method and suggested an instructional memorandum to utilize maturity measurements to meet traffic delay demands. Maturity was used to reduce the traffic delay opening time from 5-7 days to less than 2 days through the implementation of maturity measurements and special traffic control measures. Recommendations on the development of the maturity curve for each project and the location and monitoring of the maturity thermocouples are included. Examples of equipment that could easily be used by project personnel to estimate the concrete strength using the maturity methods is described.

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# INTRODUCTION

The Iowa Department of Transportation and the concrete paving industry are continuing to explore new ways to develop concrete pavement technology. One area of research focuses on finding more accurate assessment of pavement strength to reduce traffic delay due to road closures. Fast Track paving has been used for full depth paving of 6 inches (150 mm) or more in areas where early opening to traffic is the concern. Currently flexural test beams are used to determine when the pavement has reached sufficient strength to allow traffic (construction and private vehicles) passage without causing pavement damage. Standard paving techniques require 5-14 days of curing prior to opening.

A Lee County paving project provided concrete pavement construction where an evaluation of new non destructive Test NDT methods could be employed in the construction of full depth paving. The project location is the sole access for large numbers of commuters living along the roadway. People from approximately 150 homes, work in town and require the use of the highway daily. They agreed to 1-2 day road closure for paving. The county was faced with considering ways to place a portland cement concrete pavement and meet the short time of closure requirement.

During the summer of 1994, research was conducted on the use of pulse velocity and maturity meter (types of non-destructive testing, NDT) methods to identify concrete strength in a thin concrete overlay on Iowa 3 in Franklin County. The strength information gained from this project was used to determine the time of traffic opening. Implementation of this technology in full depth paving was required to move toward an NDT methodology as a replacement for physical test specimens.

## RESEARCH OBJECTIVES

The project was designed to investigate ways to reduce traffic delays through the use of NDT methods to estimate the rate and magnitude of concrete strength gain in concrete pavements under field conditions. Currently a road project of

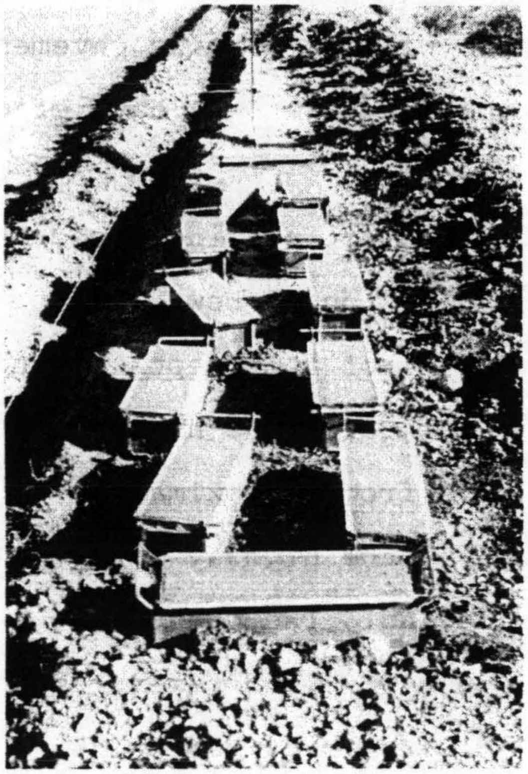

**Figure 1, Flexural Strength Test Beams**

this type would require the preparation of multiple flexural test beams or cylinders as shown in Figures 1 and 2. In this case the

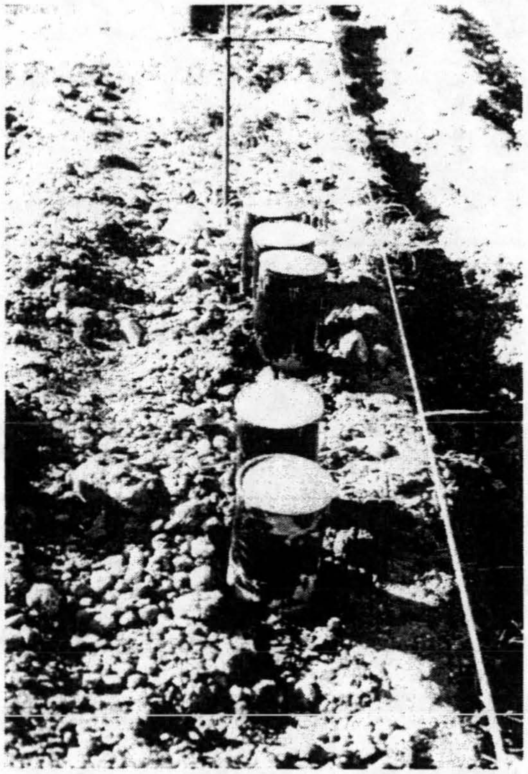

**Figure 2, Compressive Strength Test Cylinders**

test specimens are not part of the slab and the results of the testing can be affected greatly by the curing location and care, handling and transportation and the differences in testing personnel and procedures. The goals for the Lee County research were as follows:

1. Develop a knowledge base in the application of Nondestructive testing methods for the determination of pavement concrete strengths required for traffic opening.
2. Investigate possible equipment needed to effectively and efficiently monitor concrete strength gain as related to time and temperature (maturity) measurements in the field.

3. Evaluate the effectiveness of maturity measurements made at various depths in the pavement and the effect of the subgrade temperature on the rate of strength gain.

4. Identify practical nondestructive testing equipment and methods for field staff to monitor rate of strength gain for traffic opening determination.

5. Monitor visual pavement distresses (cracking and patching by type, extent and severity) on an annual basis, for two years after construction to identify the effect of early opening of pavements to vehicular traffic on pavement performance.

6. Develop an instructional memorandum for use by construction field staff and contractor personnel in the operation of selected NDT measuring devices for measurement of strength gain under field conditions.

## EXPERIMENTAL DESIGN

### *Data Collection Methods*

The research team for this project consisted of personnel from ISU with assistance from Iowa DOT personnel on the project. Data collection methods centered on the use of pulse velocity and maturity for this project. Both types of data were correlated to laboratory values for flexural and compressive strengths of the constructed pavement.

Maturity measurements were taken at the beginning and ending of each day's concrete placement with recording maturity meters. The researchers planned to utilize some form of the pulse velocity measurements at 500-ft. (152.4 m) intervals between the beginning and ending of days' placement to monitor strength gain in addition to the maturity meters.

In addition, hand held temperature and humidity recording devices were used to measure slab and air temperature and air humidity at each of the previously identified maturity meter and pulse velocity locations (500 ft, 152.4 m intervals). These devices were also used to measure strength gain in the paved shoulder construction as an NDT control for construction of the earth shoulders behind the curbs and along the pavement.

### *Instrumentation Data Collection Device Selection*

Maturity meters selected for this project were the Model H-2680, System 4101, manufactured by Humbolt Manufacturing Co. This device provides the potential for monitoring four channels or thermocouples simultaneously. Each meter can be programmed to begin recording at a user specified time, sample at a specified time interval, record time and temperature, and calculate maturity relationships in terms of time/temperature or equivalent age. It also provided the storage capacity for data of 365 days of recording and could be downloaded to most popular computer spreadsheets. It was chosen for its programming and recording abilities, number of channels and download capabilities. Figure 3 shows an example of the devices used in this project. Four such

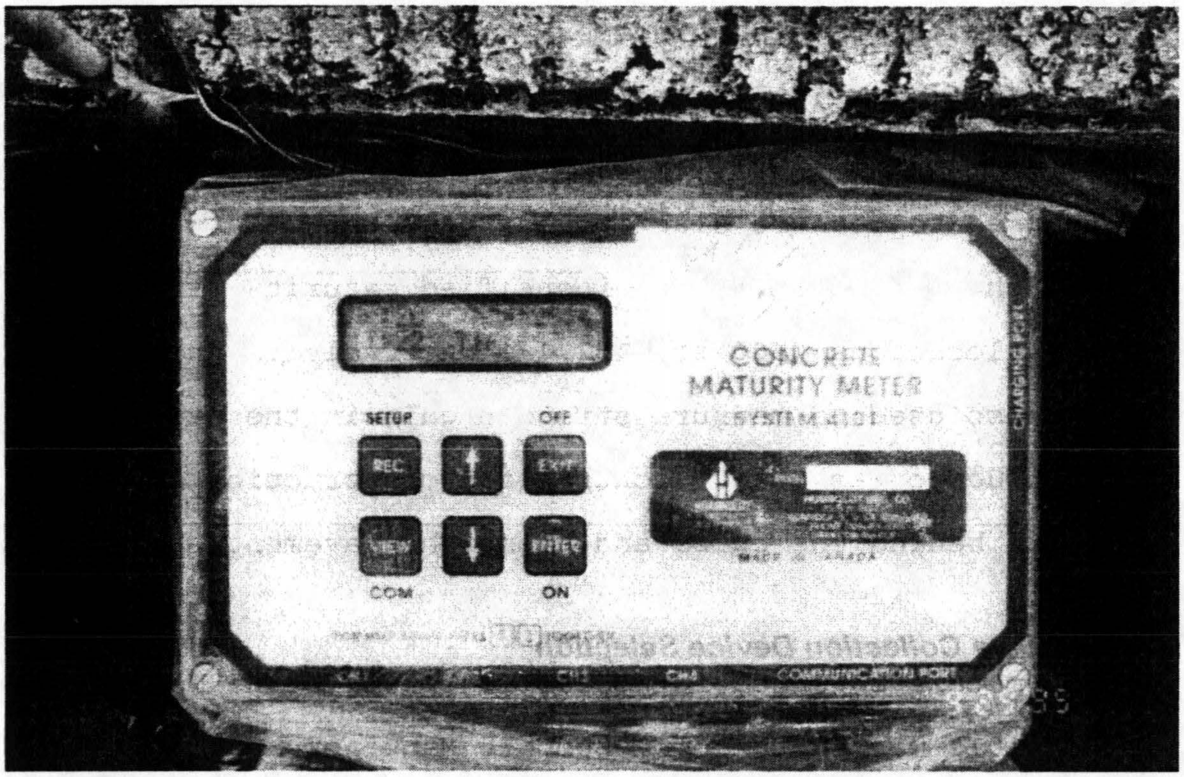


**Figure 3, Humbolt Model H-2680, System 4101 Maturity Recorder**

devices were utilized for this project. Each device came with a handy carrying case, thermocouple connectors, and cabling for downloading. The device is connected to the pavement by a simple two-pole connector and "T" type thermocouple wire. One end of the wire is attached to the connector and the other is stripped approximately 1 in. (25 mm) to allow for twisting of the metal wire ends. The twisted end of the wire was positioned on a wood dowel for the desired depth of measurement. The dowel is then inserted into the concrete to measure temperatures at a 1-in. (25 mm) and 3.5 in. (87-mm) depth. The dowel is illustrated in Figure 4.

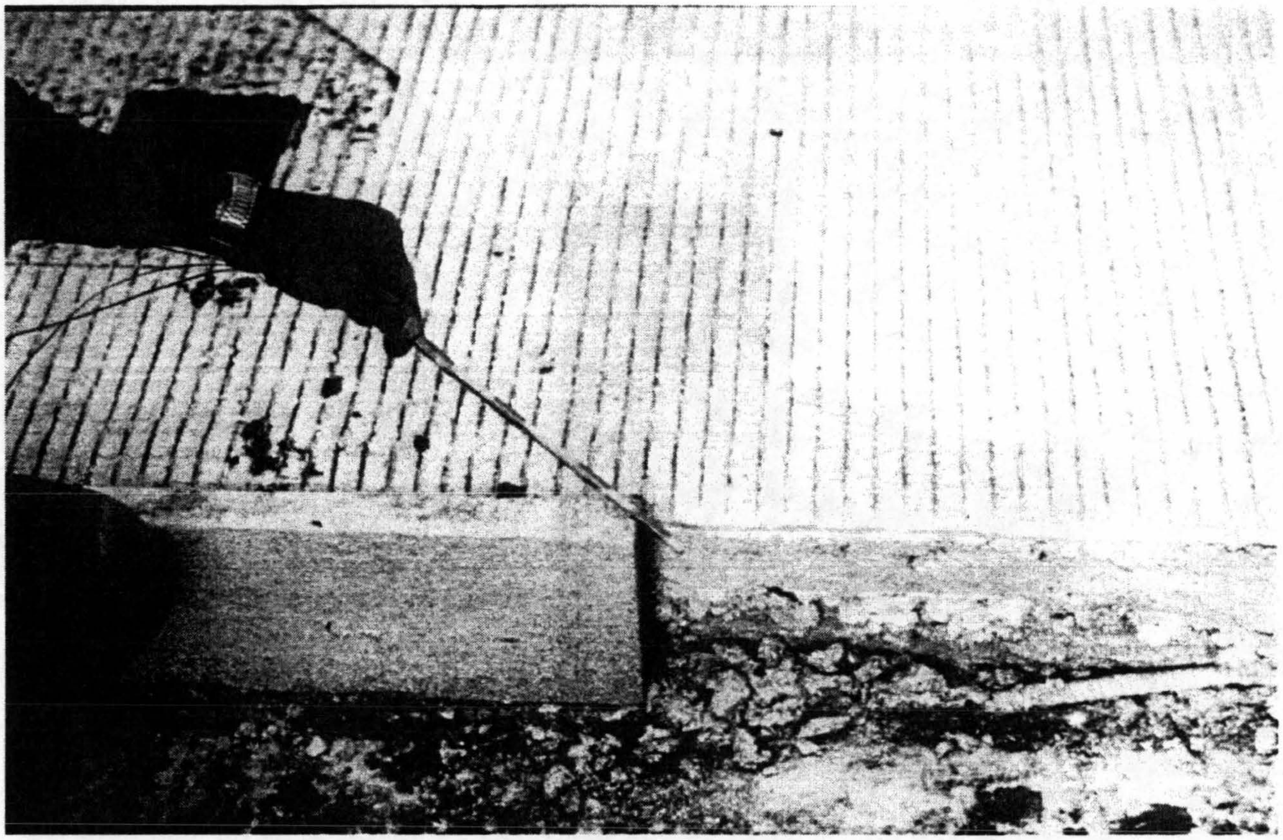

**Figure 4, Maturity Thermocouple Dowel Assembly**

Maturity temperatures were also measured with the use of digital thermometers manufactured by Omega Industries. These devices came in two models, the HH-23 and HH-25. An example of these devices is shown in Figure 5. They utilized the same type "T" thermocouple wire and connectors as used with the recording maturity meters. In the case of the Model HH-25 one thermocouple may be connected and evaluated. The Model HH-23 utilizes two connectors and can evaluate each thermocouple output or the differences between outputs. This unit also is equipped with an adapter that allows for the connection of six

**Figure 5, Omega Industries Digital Thermometer**

thermocouples at the same time.

Pulse velocity was measured with the V-Meter; Mark II distributed by James Instruments Inc. The unit is housed in a carrying case and requires a container of grease for assisting in the development of a solid contact between the sensor heads and the concrete face. This device has two transducers that must be placed in full contact with the concrete surface and pointed directly at each other. The concrete surfaces are greased to provide full contact with the transducers. The device is illustrated in Figure 6.

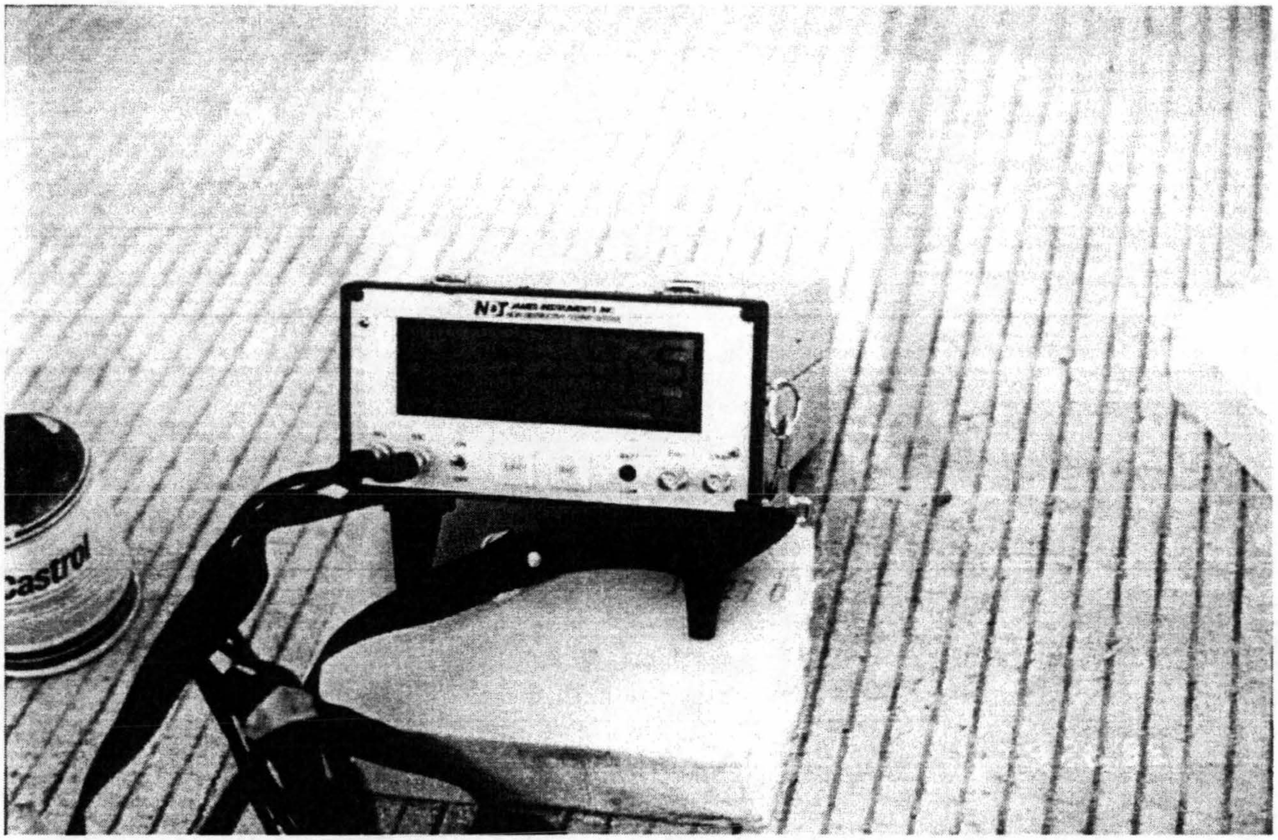


**Figure 6, James Industries Inc. Pulse Velocity Meter, Mark II**

A final device selected for this project consisted of a simple hand held temperature and relative humidity measuring instrument. The Pen Humidity/Temperature distributed by Omega was selected for this project. This device measures temperature in degrees Fahrenheit or Celsius and the relative humidity of the air at the site. It can be carried in a pocket or carrying case. It was used to provide a comparison between the air temperature and relative humidity to the temperature and maturity of the concrete at each manual temperature measurement location. An example of this device is shown below the clipboard, in Figure 7, which provides an insight into the relative size.

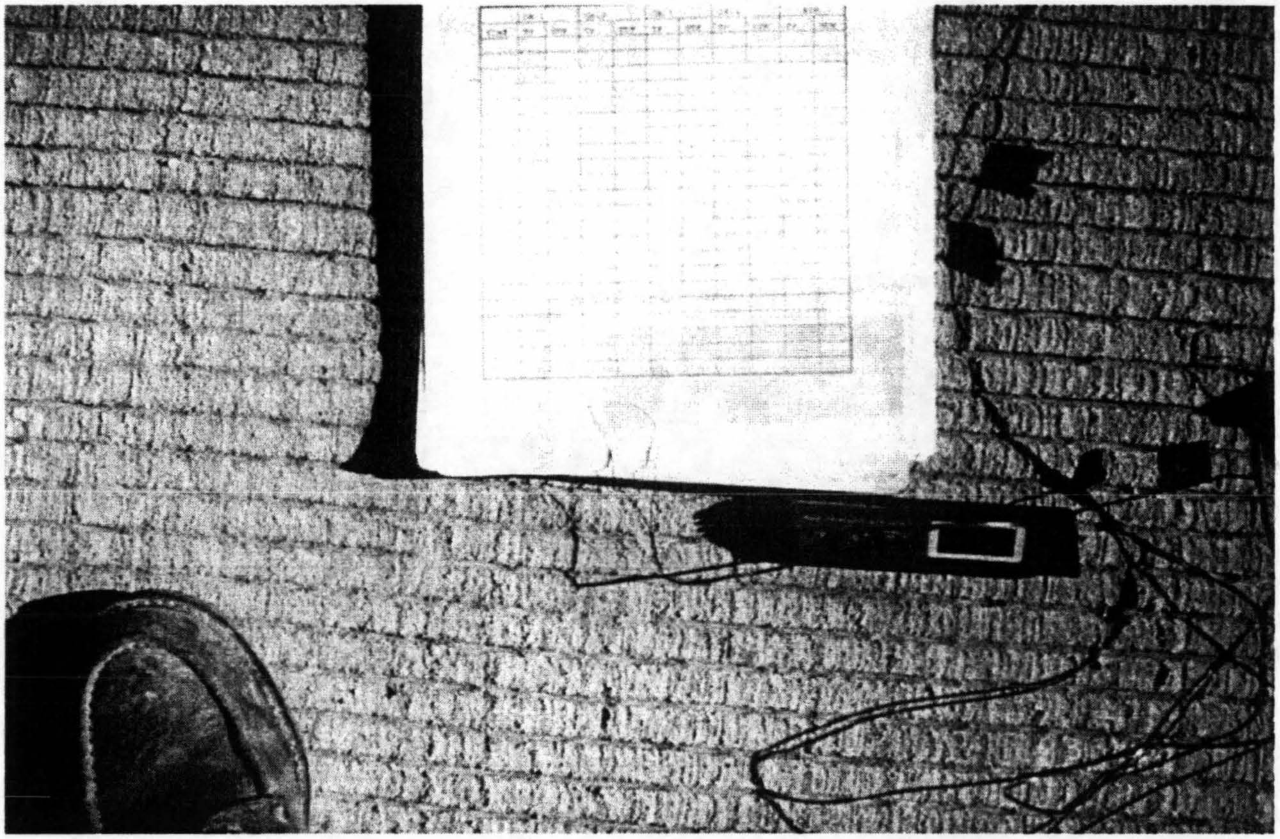

**Figure 7, Omega Industries Temperature/Relative Humidity Device**

## TEST SITE CHARACTERISTICS

### *Test Site Selection*

The Lee County project FM-56(18)-55-56, selected for this research came as a result of presentations made about previous maturity test projects and the potential for reduced traffic delay times. The county engineer contacted the research staff with regard to a desire to build a concrete pavement and reduce or eliminate the local traffic control problem during construction.

The 7.1 mile (11.43 km) project is located between Keokuk on the south and Montrose on the north. The Mississippi river and a branch line of the Burlington Northern Railroad form the east boundary and a series of bluffs form the west boundary of the highway right of way. Approximately 150 persons, who live within the project boundaries, are limited to access from either end or two interior connections on the west side of the project. Most of the residents work in Keokuk or Fort Madison and required use

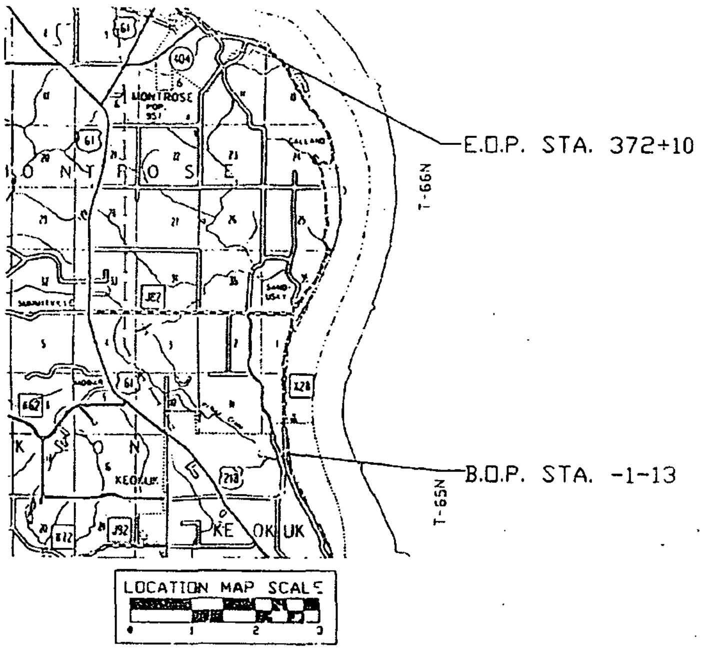


**Figure 8 Construction Project Site Map**

of the road daily. This made conventional concrete paving difficult to construct and not cause several days of inconvenience for local residents due to required curing times. The project location, shown in Figure 8 gives an indication of the lack of access points into the project and the problems that this causes for the construction of the pavement and materials handling.

After reviewing previous maturity research results and the project with the research staff, the county engineer decided to utilize maturity measurements for project control in an attempt to limit the time of local traffic restriction to less than two days. This meant that residents would not be allowed in or out of their driveways during the day of paving and until the concrete had reached a safe maturity estimated flexural strength. This provided a satisfactory traffic plan for local residents. It also provided the county with a way to reduce construction times for each portion of the paving sequence for mainline and. shoulder construction.

The site provided the research staff with the first opportunity to test the maturity concept of project control on a full depth pavement and shoulders. It represents a typical paving situation for county projects in terms of the pavement cross section and paving sequence. In this case the center portion of the pavement was to be placed 7 inches (180 mm) in depth and 22 ft. (6.7 m) in width. The concrete was placed directly on an existing granular roadway surface. In some locations the roadway had been reconstructed in the previous year for short distances to correct geometric deficiencies. Full depth concrete paved shoulders of 5.5 ft. (1.7 m) width in urban areas and 4.0 ft. (1.2 m) width in rural areas, were placed after completion of the mainline pavement. These sections were also monitored by maturity measurements.

This project was different from many county projects in that no large farms are located along the project and there was no need for truck traffic to use the project.

### NDT Preproject Preparations

One of the objectives associated with this work involved the investigation of the maturity gain over a period of greater than 24 hours. To achieve this objective it was necessary to obtain additional maturity recording devices and pulse velocity equipment. Two recording maturity meters purchased for previous research work with the Iowa DOT were coupled with two additional devices from the same manufacturer. This provided enough equipment to monitor concrete placed at the beginning or end of each day of concrete placement for at least 48 hours or 2 days before the equipment was required at a new site on the project.

Due to the anticipated speed of paving, over 1 mile (1.61 km) per day, multiple pulse velocity readings were anticipated at various locations simultaneously. A total of two pulse velocity devices were used to meet these needs.

Based on previous research in overlay construction in 1994, the research team looked at new and improved ways to develop the

1. test holes for the pulse velocity transducers to be placed in the plastic concrete. The Iowa DOT was interested in the variability and impact on strength estimation in data obtained from transducers between:

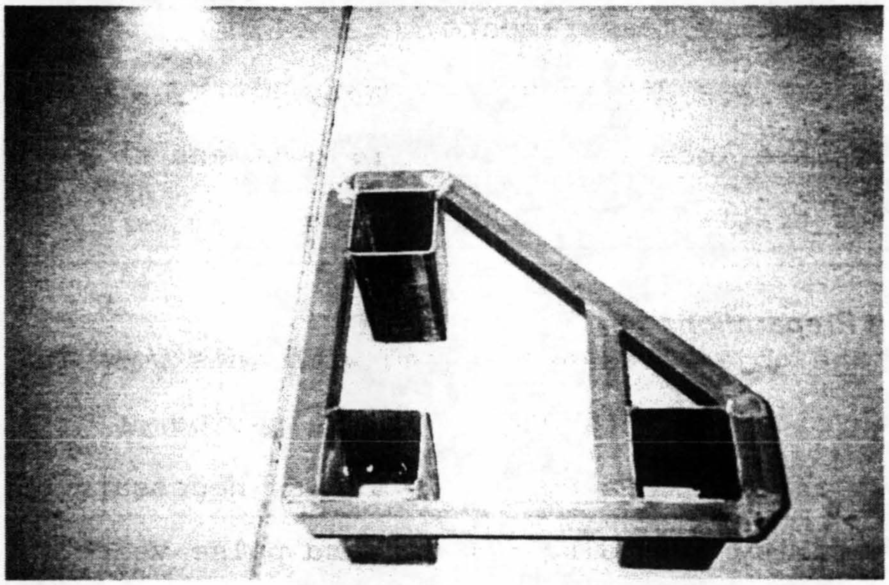

**Figure 9, Pulse Velocity Metal Access Template**

The outside edge of the concrete slab and a vertical hole 1.0 ft. (305 mm) from the edge transversely across the slab.

2. Vertical holes 1.0 ft. (305 mm) from the outside edge of the concrete and 1.0 ft. (305 mm) apart longitudinally or transversely across the slab.

In all cases the holes were located in such a manner as to allow testing to be accomplished from the edge of the concrete during its curing period.

After many unsuccessful attempts to develop a metal template that could provide three 6 in. by 6 in. (150 mm by 150 mm) square holes simultaneously, a template and individual hole devices were developed. The prototype metal template is shown in Figure 9. The weight of this device made it impractical for rapid use in the field by a single person. Figure 10 shows the wood template in place on the concrete slab. Placement was made immediately after the curing compound was placed on the slab.

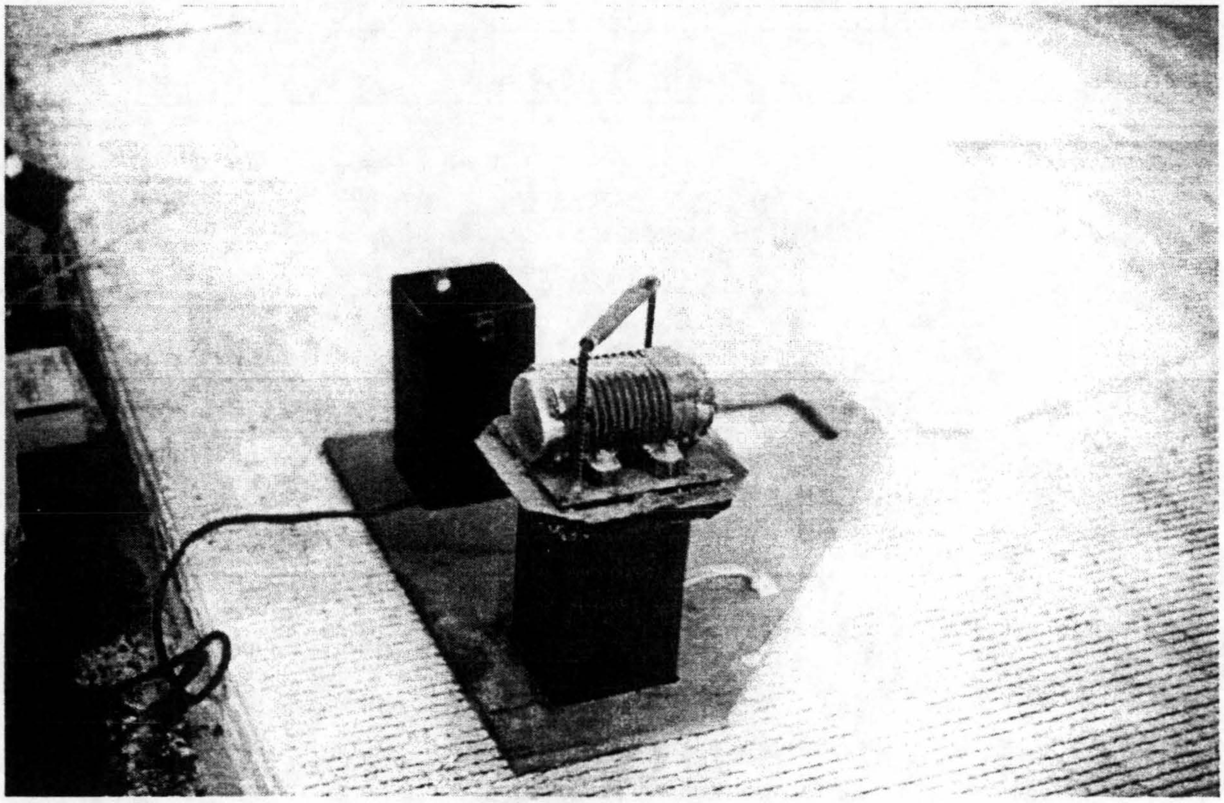

**Figure 10 Pulse Velocity Measurement Template**

Metal rectangular tubing was used to develop the test hole shaping devices. One-foot (305-mm) lengths of tubing were cut for each of the holes to be developed in the concrete to provide ample height for insertion and removal from the plastic concrete. An example of the tubing is shown in Figure 10. This figure also illustrates the positioning of the tubing over the template holes. In this figure, the driving head and vibrator are also shown. A simple truck bed vibrator and custom made driving head, powered by a portable generator were used to vibrate each tube section into the plastic concrete. Concrete form oil was placed on each side of the insert to release it from the fresh concrete. The wood template was first positioned on the slab and then the three tubes were positioned on the template. Figure 11 illustrates the template and tubes ready for insertion in the

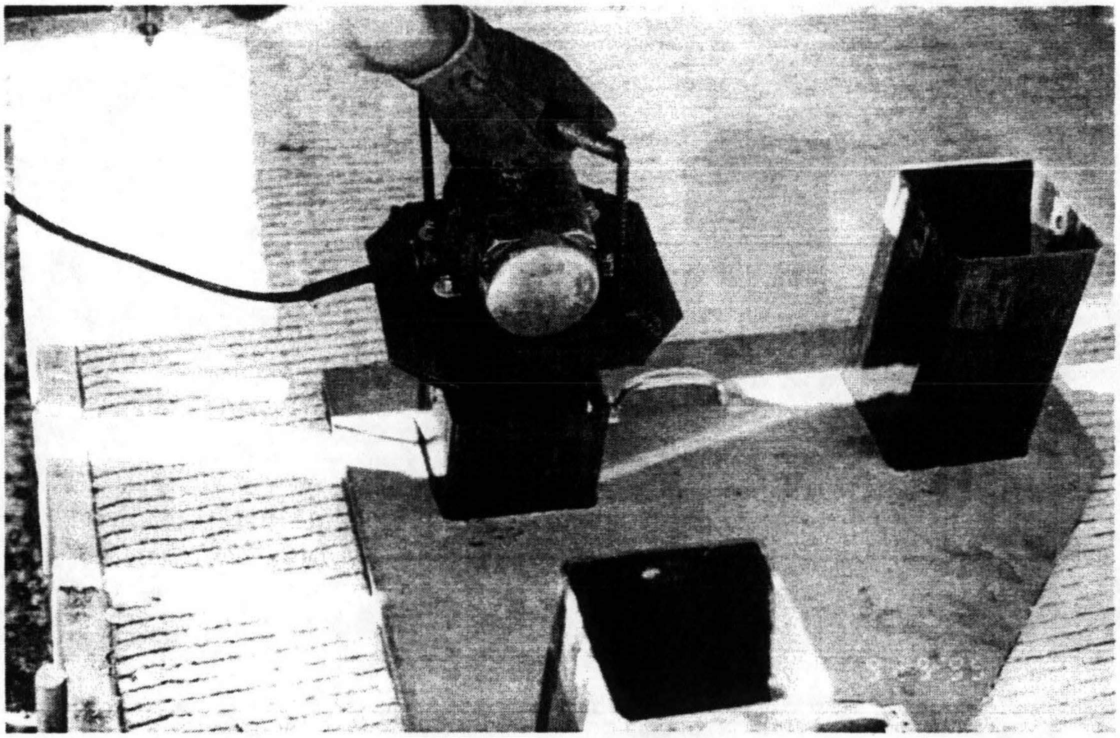

**Figure 11, Pulse Velocity Access Insertion Layout**

concrete. Next the driving head was positioned over each tube and the vibrator operated until the tube reached the bottom of the slab. Depth was measured on the side of the tube and by feel of the vibrator. In this case the use of the contractor's portable paving bridge aided access to a location directly over the access holes for driving the tubing and removing it. It also served as a way to insert the maturity thermocouple wires near the center of the pavement cross section. The metal inserts allowed for the removal of concrete from the interior of the test hole by use of a trowel or hands as shown in Figure 12. Tubing was removed upon removal of the concrete from the pavement in each test hole.

**Figure 12 Pulse Velocity Test Concrete Removal Methods**

The form tubing was removed by extracting it vertically as shown in Figure 13. A custom built handle was inserted into holes near the top of the tubing on opposite sides. This method worked very well when the tubing was well oiled prior to insertion and pulled vertically after the concrete was removed. The result was a four sided, smooth walled hole that provided good contact for the transducers.

**Figure 13 Pulse Velocity Test Tube Extraction**

Pulse velocity measurements were taken by attaching the two geophones to the readout device, greasing the geophone heads and positioning them in two adjacent holes with the heads pointing at each other. The grease served to make an airtight contact with sidewall of the hole and prevent adhesion of the concrete with the device. This test is illustrated in Figure 14. Note the presence of insulation blocks on the pavement. These were inserted in the access holes during the time between pulse readings to assure the retention of temperature and moisture in the walls of the access holes. Upon completion of the pulse

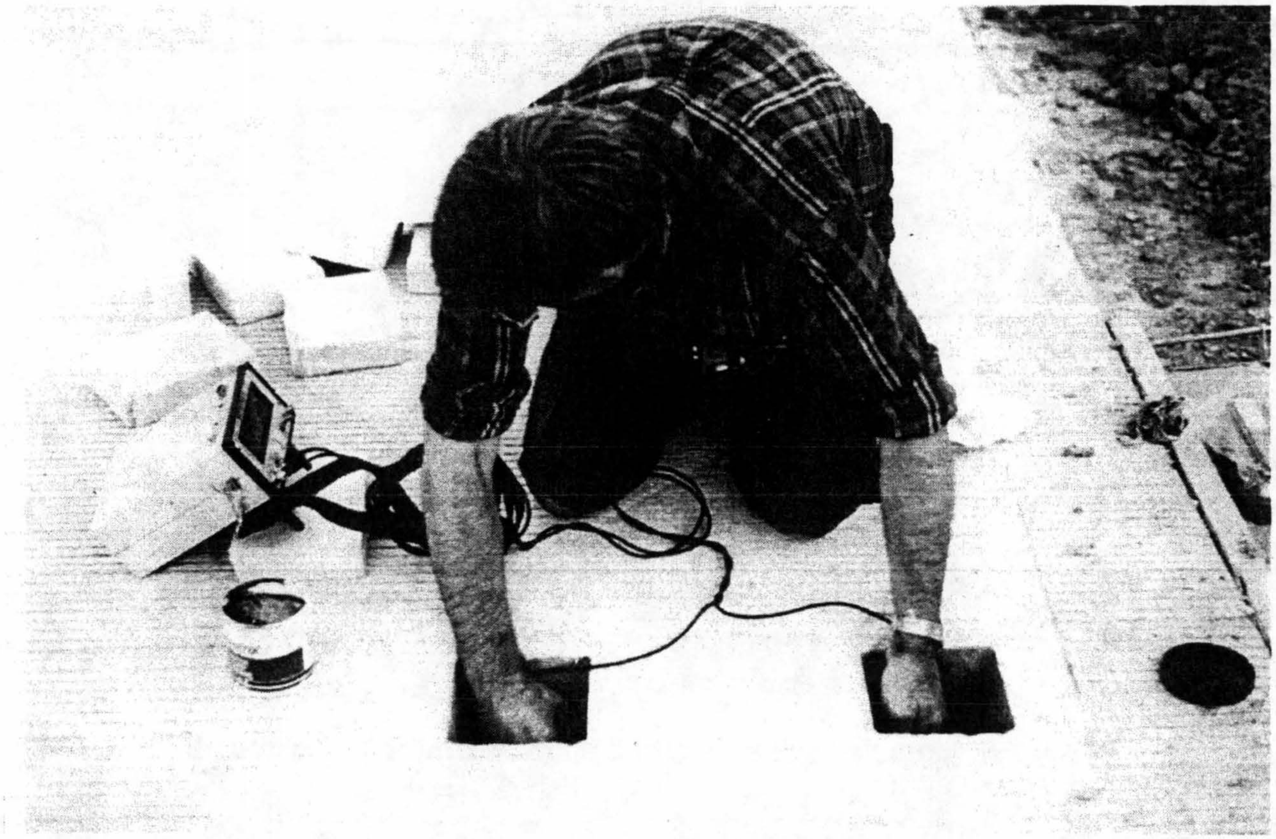

**Figure 14, Pulse Velocity Measurement Activity**

velocity measurements, the access holes were filled with concrete from the paving operation by members of the research team. One of the major problems with the pulse velocity measurement process was the access to the pavement area. Figure 15 illustrates the amount of equipment required to develop the access holes for the test. In addition to this equipment the pulse velocity meter had to be moved between test locations. There was insufficient room on the road shoulders to move the equipment by vehicle and the actual movement resulted from human packing or attaching the generator to the contractor work bridge. This option required work by two or more persons to transport

**Figure 15, Pulse Velocity Access Preparation Equipment**

the equipment along the roadway. As a result of these constraints and the inconsistent results, the method was terminated early in the construction.

Preparations for the development of the maturity relationships included laboratory testing of the field mixed materials. Previous research had developed laboratory maturity relationships (temperature/strength vs. time from placement) prior to construction. This project concentrated on transferring that activity to the field and the first day of paving.

Laboratory tests were conducted utilizing both the maturity and pulse velocity equipment. Both flexural test beams and compressive cylinders were cast to measure strength gain. A maturity meter served as the base measurement device for time and was connected to a compressive cylinder and flexural test beam with a "T" thermocouple. Additional beams and cylinders, cast from the same mix batch, were tested for strength at predetermined times. The pulse velocity was measured transversely across each specimen prior to destructive testing, and recorded with the measured maturity at each test. This activity resulted in a maturity curve relating concrete strength to curing time required to meet the 350 psi (2.41 MPa) and 500 psi (3.45 MPa) Iowa DOT flexural strength targets for this project.

Similar preparations were made at the field concrete plant site. At this location, a test pit was built to house the flexural beams in wet sand. Beams and cylinders were cast from a randomly selected load of concrete. The load was selected from the trucks after the paver achieved a steady rate of movement from the header for the day. This represented the consistent flow of concrete from the plant and an acceptable sample of what was being delivered to the grade. The cylinders were transported to the Southeast Iowa Transportation Center for curing and testing at predetermined times due to the availability of testing equipment and pulse velocity meter. One of the flexural beams in the sand pit was connected to the maturity meter by the thermocouple wire. Flexural testing was accomplished at the field laboratory of the Iowa DOT. This provided strength/time relationships that could be compared to laboratory results and considered for future project control methods.

Other preparations for field installation of maturity measuring devices included the development of thermocouple leads and meter connections. Each of the meters is equipped with one or more pairs of receptacles for a two pole plug. The plug is attached to the thermocouple on one end and the wires on the opposite end are stripped for approximately 1 in. (25 mm). The stripped end is braided for insertion in the concrete. The probe end of the wires was taped along a 7 in. (180 mm) wood dowel rod at locations near the bottom end, the middle and 1 in. (25 mm) from the top end. Care was taken to not place tape on the braided portion of the sensor.

The research team established sensor locations along the rod to allow testing at 500 to 1,000 ft. (152.4 to 305.0 m) intervals. Temperature data was required at each location to establish a temperature gradient throughout the depth of the concrete. The top sensor can also be used to control the time of joint sawing or preparation. The attachment of the connectors to the wire requires time and effort due to the small size of the wire and connector screws. Lead wire lengths were established based on the lateral location in the slab where they were to be placed. This included locations at 1 ft. (305 mm) and 11 ft. (3.4 m) from the edge of the pavement.

Maturity meters were preset to time zero and a datum temperature of -10 Celsius. Laboratory relationships between concrete flexural strength and construction curing time were made available to the field data collection team. This provided a way to determine when the concrete had reached sufficient strength to allow opening to local cars and to construction traffic for the next phase of the project.

Maturity thermocouples were placed near the centerline of the pavement with the aid of the construction work bridge as shown in Figure 16. Lead wire lengths were cut to allow for readings to be taken from the pavement edge for these sites.

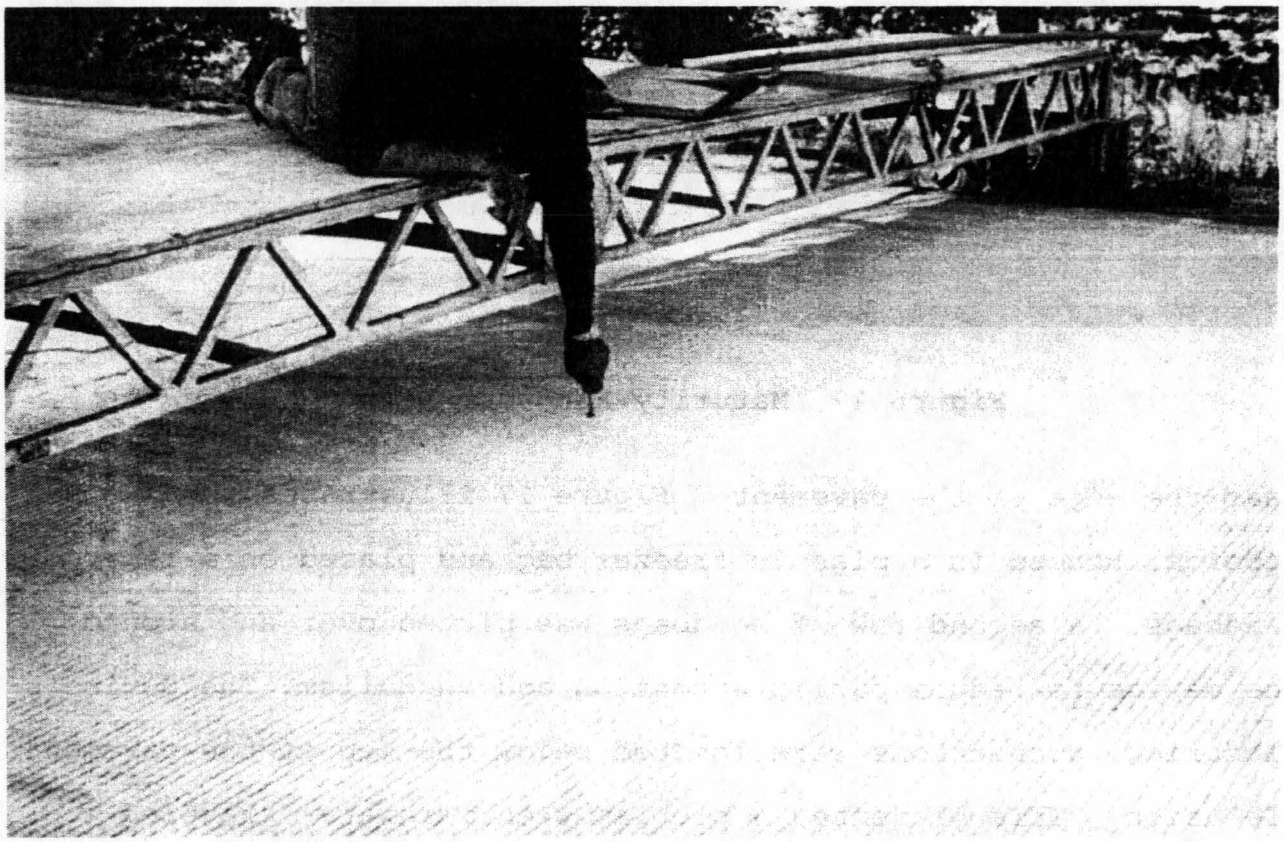

**Figure 16, Maturity Thermocouple Installation**

The sites established for the use of the recording maturity devices were developed in the manner shown in Figure 17. Thermocouple wires were attached to the recording device located

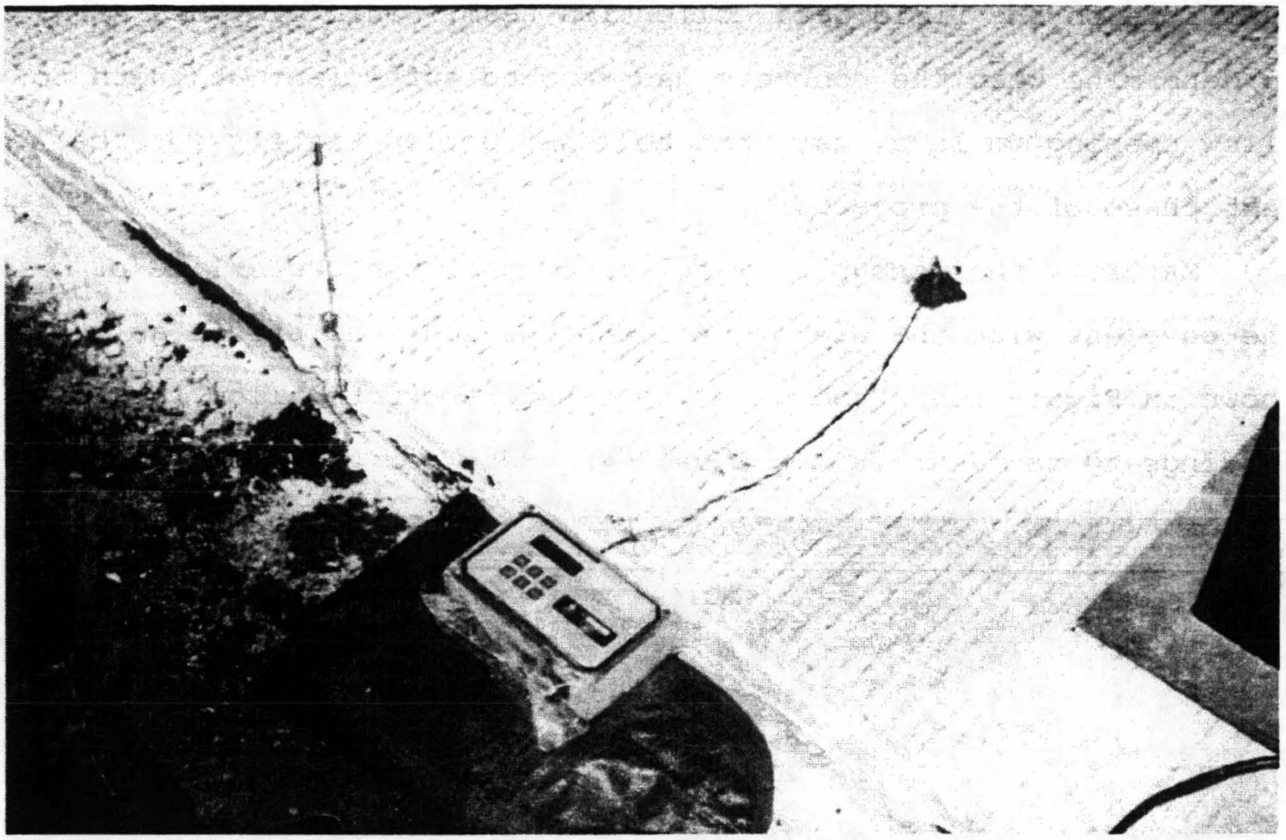

**Figure 17, Maturity Recorder Layout**

near the edge of the pavement. Figure 17 illustrates the recorder housed in a plastic freezer bag and placed on a layer of sandbags. A second row of sandbags was placed over and around the device to reduce public attention and vandalism. The device's electrical connections were located below the top of the pavement elevation. This presented a problem when rainwater traveled along the wires and shorted the electrical system.

Use of the handheld digital thermometers allowed the research staff to collect large amounts of maturity data quickly. Sites were marked with a paint stripe or circle on the pavement for rapid identification. Figure 18 illustrates the use of the

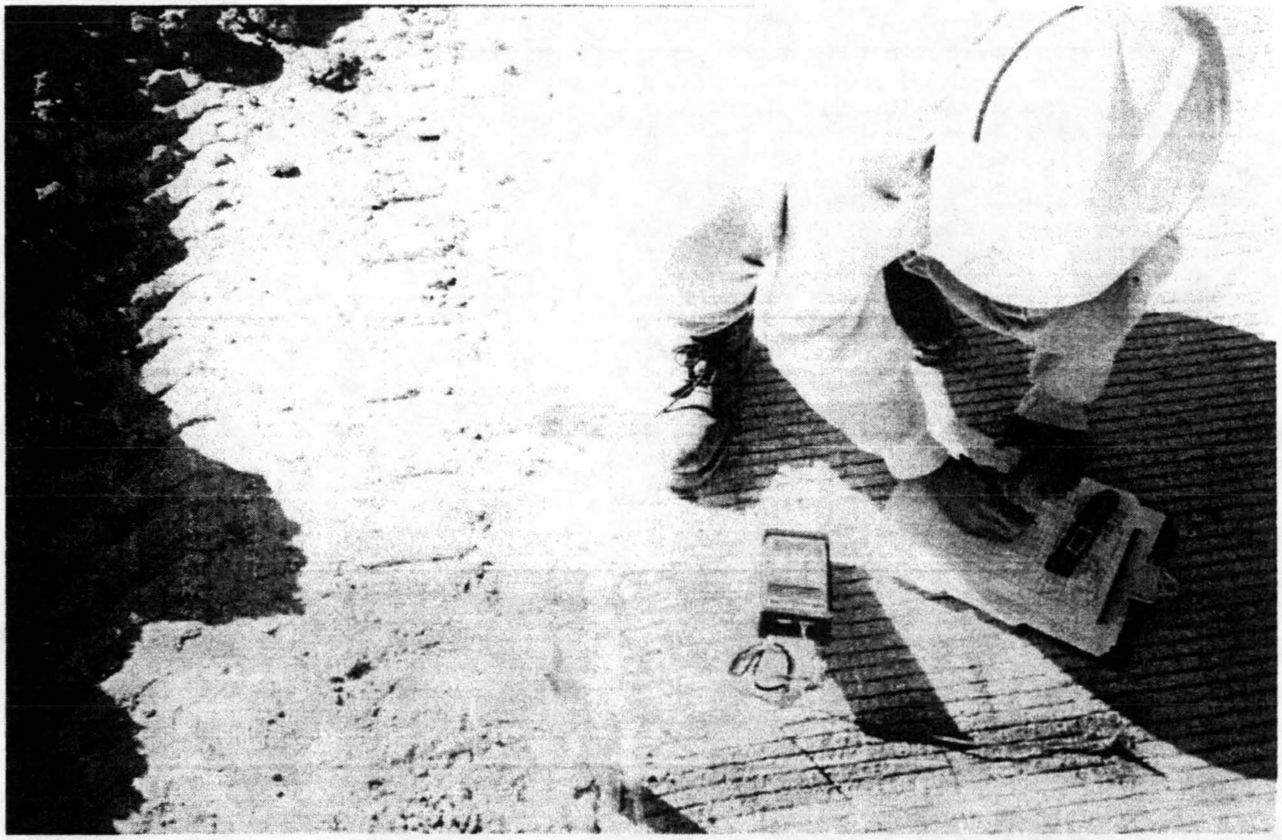

**Figure 18 Manual Maturity Measurement**

thermometer to collect data at one of these sites.

A full test site setup including the pulse velocity access points, and the maturity probes with one in a test beam at the site are shown in Figure 19. This provides a view of the amount of work that was required by the research staff to accomplish this effort.

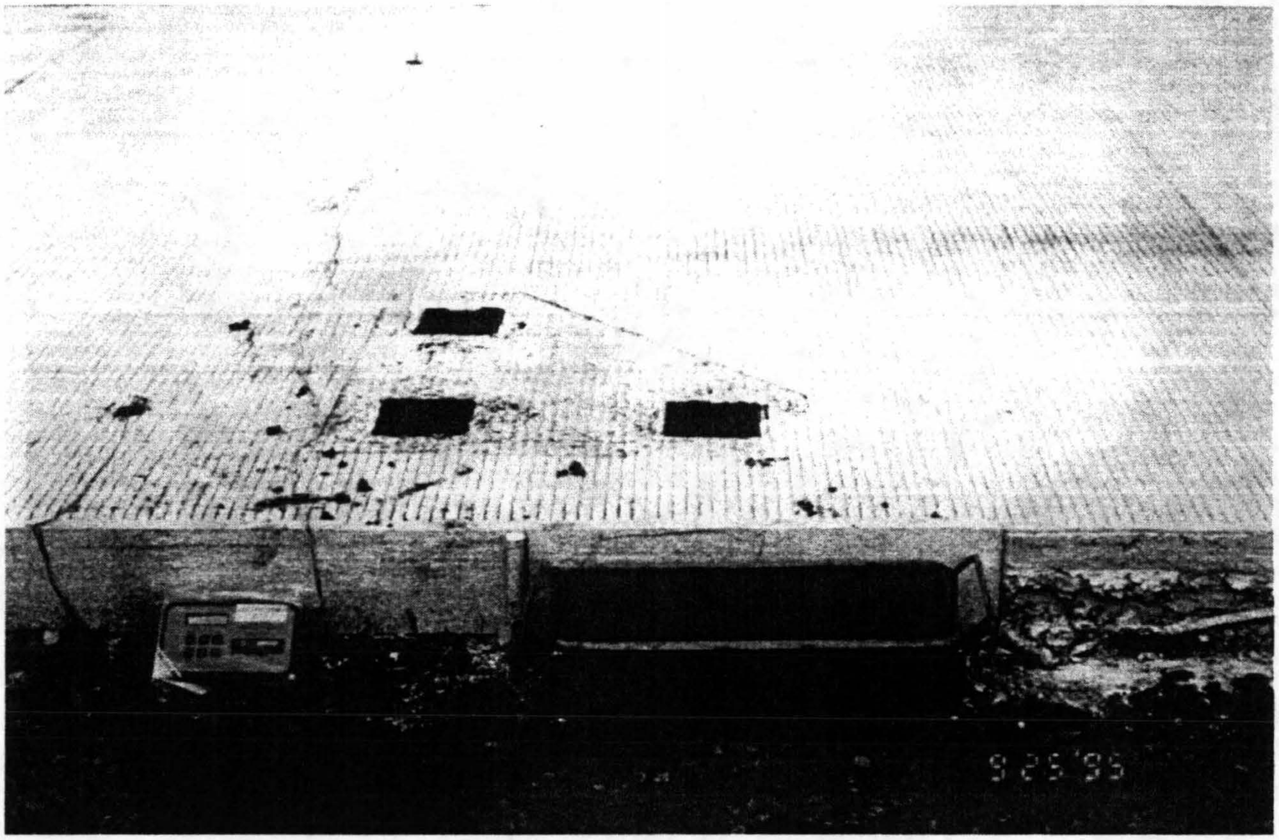


**Figure 19, NDT Site Layout**

## CONSTRUCTION SITE ADMINISTRATION

The construction project was under the supervision of the Lee County Engineer, Dennis Osipowicz P.E. The county inspection staff consisted of Ernie Steffensnmeier, Howard Spiez, and various other county staff at alternate times during the construction. Jim Cable represented ISU on the project. Field operations for ISU were carried out by Jim Riensche with a large amount of assistance from Jennifer Ries and Shane Tymcowicz of the Office of Materials, Iowa DOT. Iowa DOT Central Materials Office and the Southeast Iowa Transportation Center Materials Staff provided assistance in the development of the maturity relationships.

Maturity data collected by the ISU staff on the project was shared with the Lee County inspectors present on the site as it was collected on the central slab construction. Lee County inspectors made the decisions on when to open a day's construction to traffic and conducted all the direct communications with the contractor, based on the data provided by the ISU staff. The ISU staff trained the Lee County staff on the use of the hand held temperature and temperature/humidity devices for use in the project control of the concrete and earth shoulder construction. County staff assisted ISU during this part of the construction by gathering additional research data.

## CONSTRUCTION PROBLEMS

The project was designed and contract documents were developed to provide for construction during the warmest months of the construction season (June through August). In this way the maximum benefit of the sun and long periods of warm temperatures could be utilized in the development of rapid curing and strength gain desired in he maturity concept for acceptance and traffic use. Pavement construction in the southeast corner of the state usually occurs early in the spring or late in the fall due to the difference in temperatures available.

In this case the contractor suggested paving in early May or in late August and September being associated the company's other paving work in the area. Due to scheduling conflicts at ISU and the county, the later date was selected. Normal weather delays postponed paving construction until late September. Paving of the center portion of the pavement started on September 25 and was completed on October 5, 1995.

No particular problems were noted in the paving operation that impacted the monitoring effort. Temperatures remained relatively high during the daytime hours and the location of the highway sheltered it from cool winds during the nighttime hours. Strength gain remained steady even though not as fast as anticipated in the laboratory. Good contractor, county, DOT and ISU relations made the project proceed very smoothly to completion.

The speed of paving and the accessibility to various parts of the project did make data collection more difficult. The lack of access roads at the end of each mile and the narrow shoulders did not allow for full size vehicles to traverse the project during concrete curing. The research team was able to minimize the problem with the rental of a small four wheel drive vehicle to navigate the shoulders and new pavement area prior to full vehicle access. A John Deere "Gator", shown in Figure 20 was found to be very helpful to the research team and county

**Figure 20, Data Collection Vehicle**

personnel for movement of testing equipment and supplies along the length of the project. It allowed for collection of large amounts of maturity data in small amounts of time.

Due to the timing of the project some problems were identified in the availability of research personnel. This contributed to problems in conducting the tests at the predetermined locations. The contractor was able to make the 1+ mile per day (1.6 km) paving pace. Due to the lack of available shoulder space and limited personnel, the movement of the generator and pulse velocity equipment was very difficult. This pointed out the importance of the maturity concept and the ease at which the thermocouples can be inserted into the concrete and the data collected over any time interval with a simple thermometer and notebook in the hands of an inspector. As the construction area increased over several days, the gator allowed the research team to monitor many locations in a matter of an hour.

## RESEARCH RESULTS

### *Maturity and Pulse Velocity Relationships*

As previously noted, samples of the materials to be used in the concrete mix were brought to Ames and used to develop a laboratory relationships between the elapsed time from placement vs. concrete temperature and concrete strength (flexural or compressive) and pulse velocity. Time, temperature and the strength relationship comprise what is referred to as maturity of the concrete in terms of time-temperature factor or equivalent concrete age. Ten flexural test beams were constructed and nine were broken as part of the test. Previously noted compressive strength cylinders were not cast as part of the laboratory work. The resulting relationship between modulus of rupture and curing time under center point loading is shown in Figure 21. This graph indicates the design strength of 350 psi (2.41 MPa) could be reached at approximately 80 hours under laboratory conditions. The area under the time-temperature curve for 80 hours of curing under cool laboratory temperatures represented approximately 1000 degree-hours of maturity. The maturity data collected in this

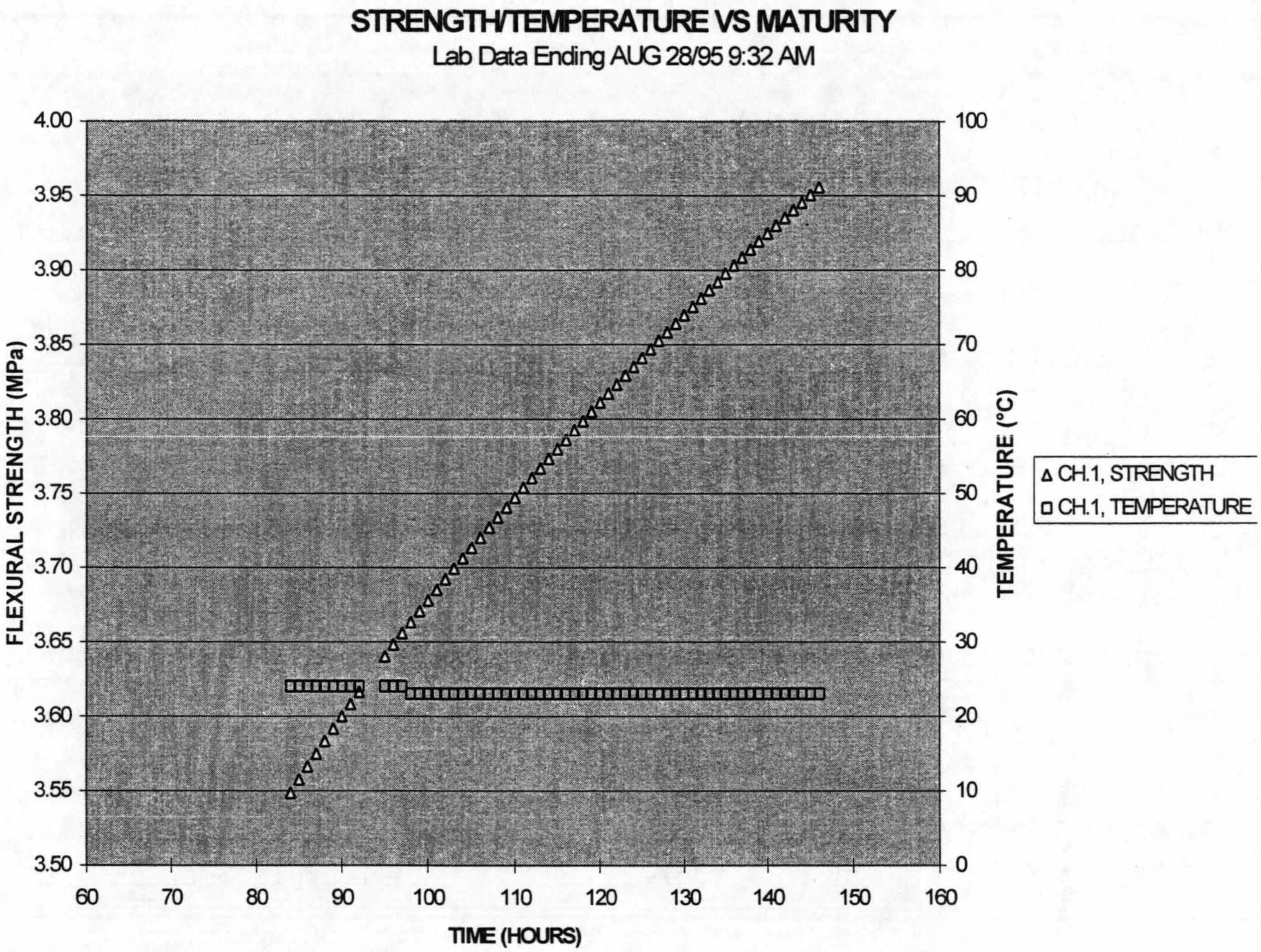


**Figure 21 Laboratory Flexural Strength vs Maturity Relationship**

test also indicated for example, if the temperature in the concrete could be maintained at 60 degrees Fahrenheit (15.5 degrees Celsius) for approximately 17 hours, the concrete pavement could be opened to car only traffic. Due to the fall paving dates, temperatures were reduced at night and the total amount of time necessary to meet the requirement for maturity was extended to 20-24 hours.

Laboratory tests to relate concrete time and temperature 3rd point flexural strength and compressive strength were not conducted as part of the reconstruction testing on this project. As a result, the comparison of 3rd point loading and center point loading of flexural test specimen strengths could not be made.

Concrete compressive strength test cylinders were made in the field and tested at the Southeast Iowa Transportation Center staff during the course of the construction. One cylinder was connected to maturity meter for data recording. Pulse velocity was measured on each cylinder prior to compressive testing. The results of the maturity measurement vs compressive strength are shown in Figure 22. Compressive strengths of 16.72 MPa and 23.99 MPa correspond with 350 and 500 psi flexural strengths that were specified for this project. It also indicates that the required opening strength for cars only was reached in 1000 degree-hours. Figure 23 represents the relationship between pulse velocity measured in the lab at the time of cylinder testing and the compressive strength of cylinders. The relationship between pulse velocity and compressive strength was supported as shown with a good relationship. The same data did not provide a positive relationship to curing time. This type of measurement appears to be very dependent on the moisture content of the specimen and the general way the specimen is cured and handled after construction.

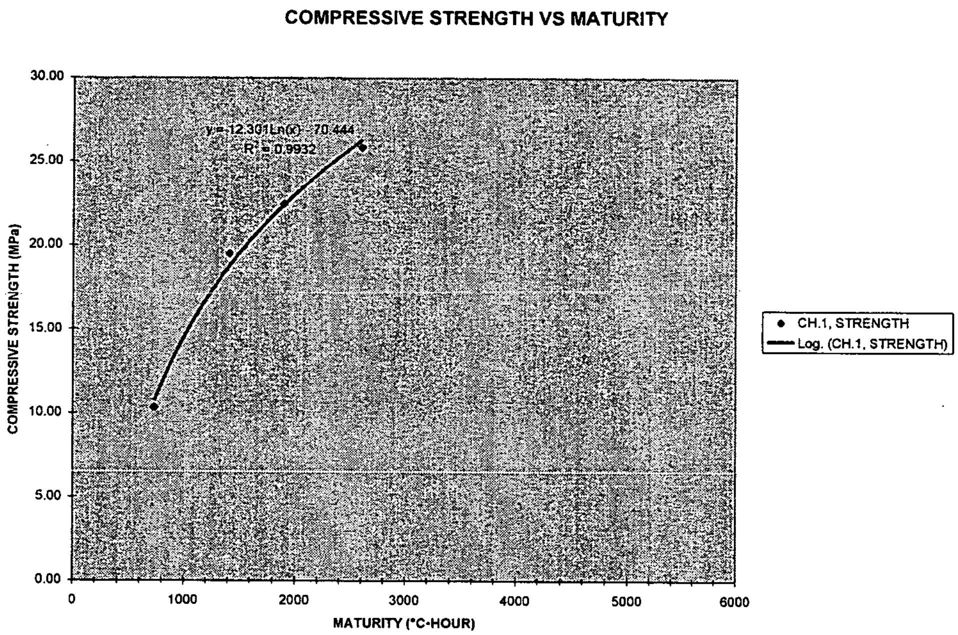


Figure 22, Laboratory Compressive Strength vs Time Relationship

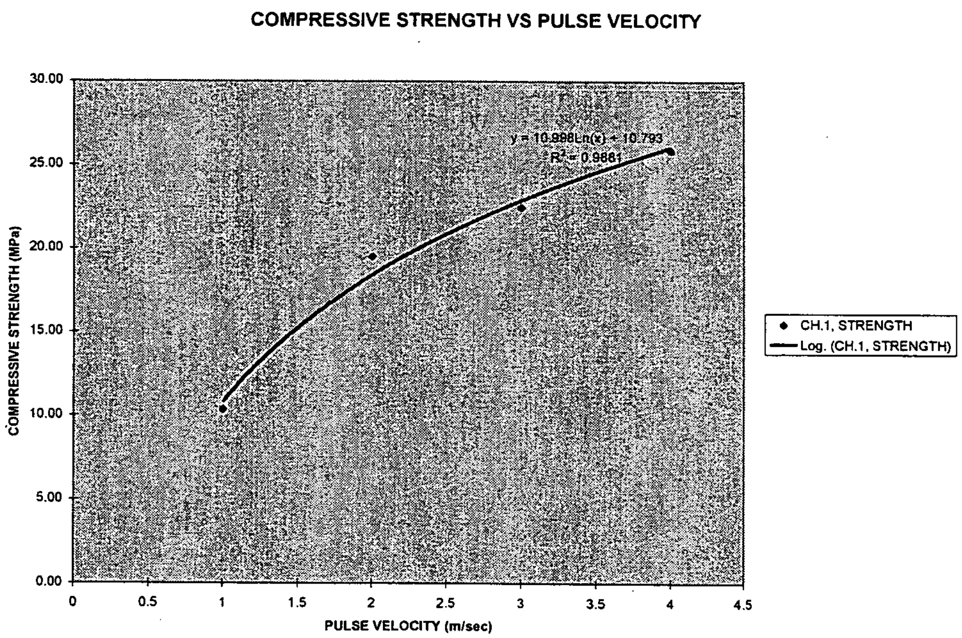


Figure 23, Laboratory Compressive Strength vs Pulse Velocity Relationship

Use of this measuring device requires a large amount of training in the settings to be used in conducting measurements.
If the pulse velocity switch and gain switch is not set at "high", the calibration and data collection for this type of measurement are very difficult to obtain. Field experience on this project indicates that significant differences can be obtained in data from two different meters utilized in the same test holes, only minutes apart.

## *Field Measured Concrete Strength Relationships*

### Maturity Results

The following items of work were performed during the pavement construction by the research team members and representatives of the Iowa DOT and Lee County:

1. Ten flexural beams were cast from a randomly selected truckload of concrete on day one of the concrete placement for use in development of the maturity curve. Since no changes in the mix design or material sources were required during the construction, no additional such testing of this type was required. The ten test beams cast for this test were in addition to the normal record requirements currently in place by the Iowa DOT and Lee County for internal record purposes. Test beam molds and a testing apparatus were obtained the Iowa DOT. Due to the loss of the wire connection between the

test beam constructed on day one and the recorder, a second set of beams was constructed on day three of the construction and these flexural beams were used to identify the maturity control strengths for the construction project. Construction and testing of the research flexural beams were accomplished by ISU staff using Iowa DOT testing equipment. The test beams were stored in a wet sand bed near the project inspection trailer and a recording maturity meter was attached to one beam and housed in the trailer for to prevent loss or damage. Beam breaks were made at times that represent 8, 12, 24, and 48 hour curing periods under field curing conditions.

A laboratory test was conducted with the project materials at the Iowa DOT Central Laboratory, prior to the construction. The test conducted in August of 1995 indicated that 350 psi (2.41 MPa) could be attained with a combination time-temperature value (TTF factor) of 700 degree C-hours.

The results of the project control test are shown in Figure 24. The graph indicates that the desired minimum strength of 350 psi flexural (2.41 MPa) strength was reached in approximately 24-26 hours under the field conditions. The project staff was able to use this relationship throughout the project for mainline and shoulder opening decisions because no changes in materials were introduced

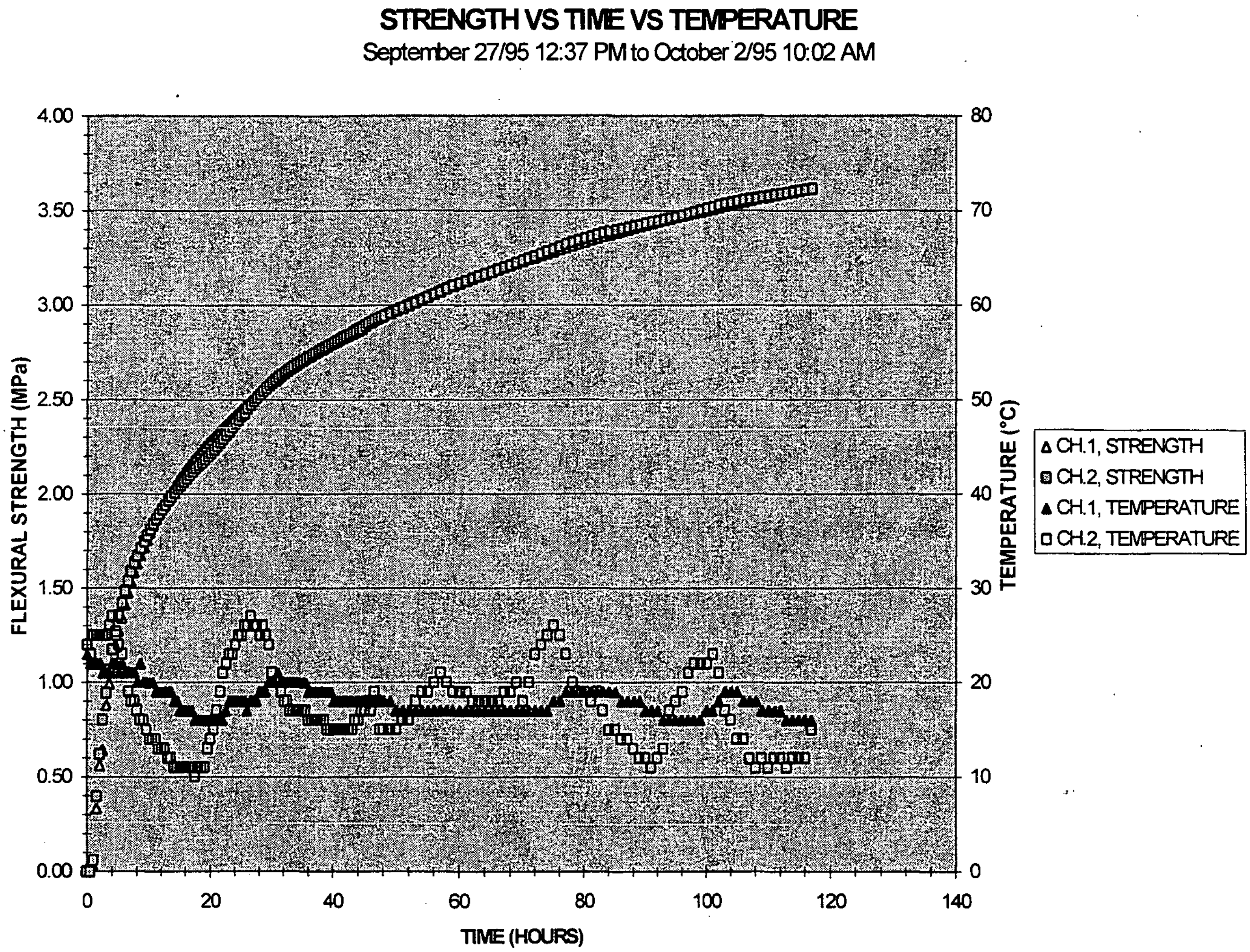


**Figure 24, Field Maturity Curve**

during the construction.

2. Strength gain in the actual pavement sections was monitored through the use of pulse and maturity meter measurements for each day's concrete placement by the research staff. The Iowa DOT staff assisted in the development of the target flexural strength to used for pavement opening decisions. Concrete cylinders were cast at the plant site while the flexural test specimens were sent

to the Southeastern Iowa Transportation Center to determine the relationship between the pulse velocity or maturity values and compressive strength. The results of the plant site flexural strength/maturity relationship was used as a guide for evaluation of on site maturity measurements for a given section at any given time to advise the construction inspection staff of the estimated pavement strength. Pavement traffic opening decisions based on this information from the research staff were made by the Lee County construction staff.

Temperature measurements used to calculate maturity for opening were obtained from a location near the edge of slab and at the following slab depths with a maturity meter:

a. Top one inch (25 mm) of the pavement

b. Middepth, 3.5 inches (90 mm) of the pavement

c. Six inches (150 mm) below the top of slab

d. Surface of subgrade, 7 inches (175 mm) below the surface of slab

This type of installation was made at the beginning and end of the days' placement of concrete. Similar measurements were taken with a separate maturity meter:

a. One inch (25 mm) below the surface at midpanel location and near centerline joint

b. Middepth 3.5 in. (90 mm) below the slab surface at midpanel location and near centerline joint.

This effort was aimed at determining a single location that would best represent the rate of slab strength gain and relate that to locations near the edge of the pavement that are easily monitored by field staff. The different depth points were used to gather data relative to the temperature gradients throughout the depth of the concrete during the development of strength gain. The results were aimed at both establishing a time window for sawing and a knowledge of the differences in strength of the concrete at various depths as it relates to the opening of the surface to traffic.

Hand held temperature measuring devices were used at regular intervals of 500 ft. (152.4 m) locations at the edge of the pavement and at the 1 in. (25 mm) and 3.5 in. (90 mm) depths in the slab. Research team staff monitored these multiple times daily as time permitted to establish the rate of strength gain of various sections of the pavement. The results of that data were used to develop a project wide relationship of maturity and estimated flexural strength. The paving of the mainline was completed in less than two weeks and the shoulder paving was completed in two weeks. The maturity data is available in tabular or graphical form for each of the self recording and handheld recording stations utilized on the project. The data from each of the maturity test sites was combined to develop a mathematical relationship between the flexural strength, time of curing and the relative humidity. The results of those measurements are illustrated in Figures 25 through 27 for the mainline paving and 28 through 29 for the shoulder paving.

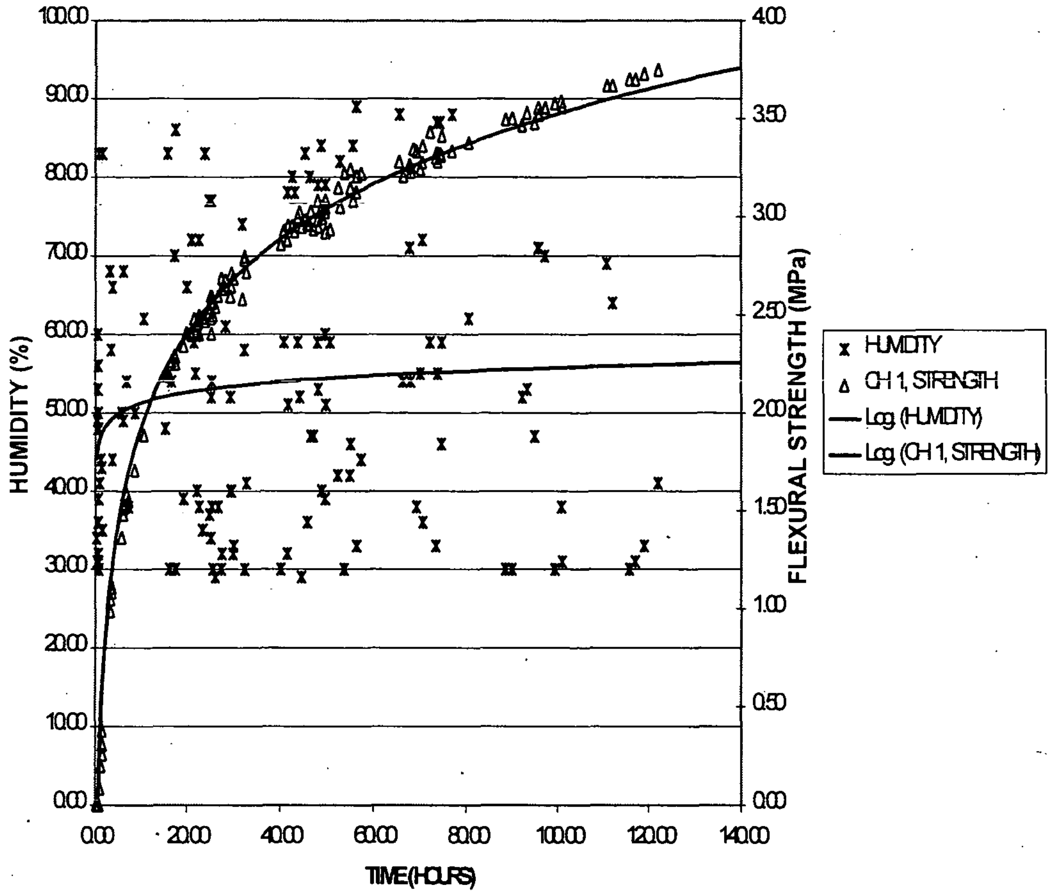


Figure 25, Maturity Strength vs Cure Time vs Humidity (Top of Slab)

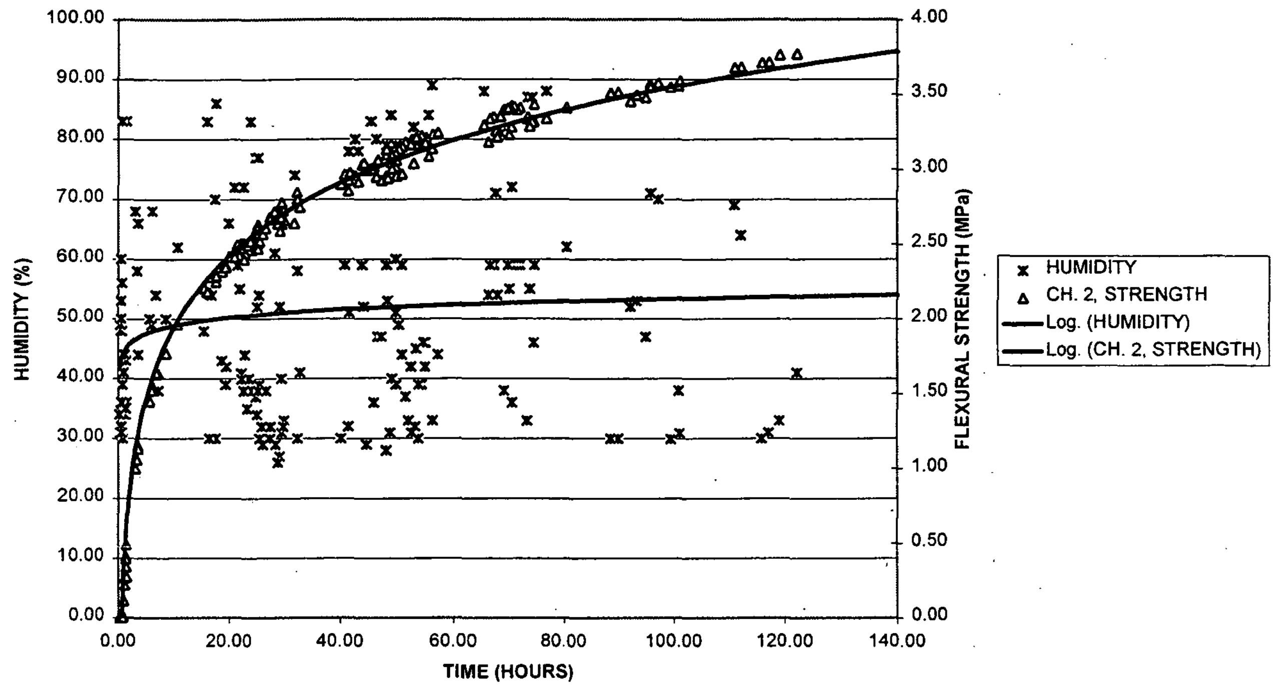


Figure 26, Maturity Strength vs Time vs Humidity (Midslab)

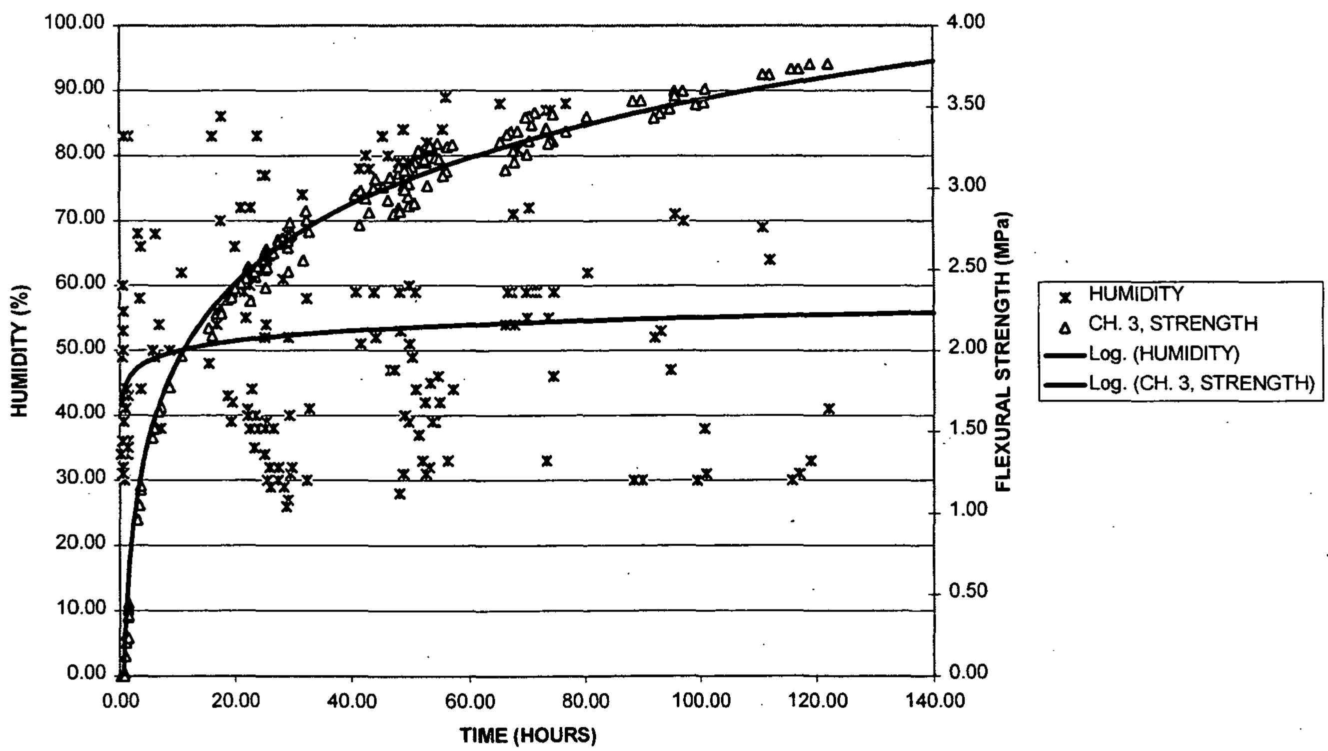


Figure 27, Maturity Strength vs Time vs Humidity (Bottom of Slab)

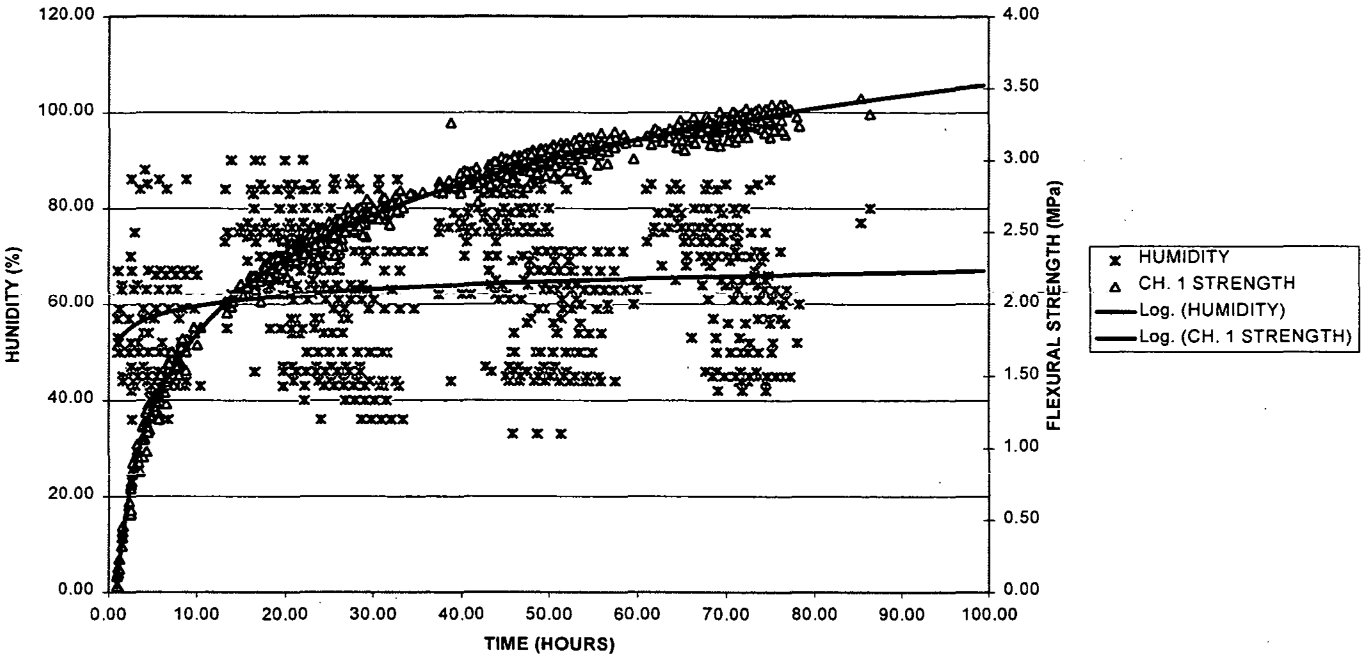


Figure 28, Maturity Strength vs Time vs Humidity (Top of Shoulder)

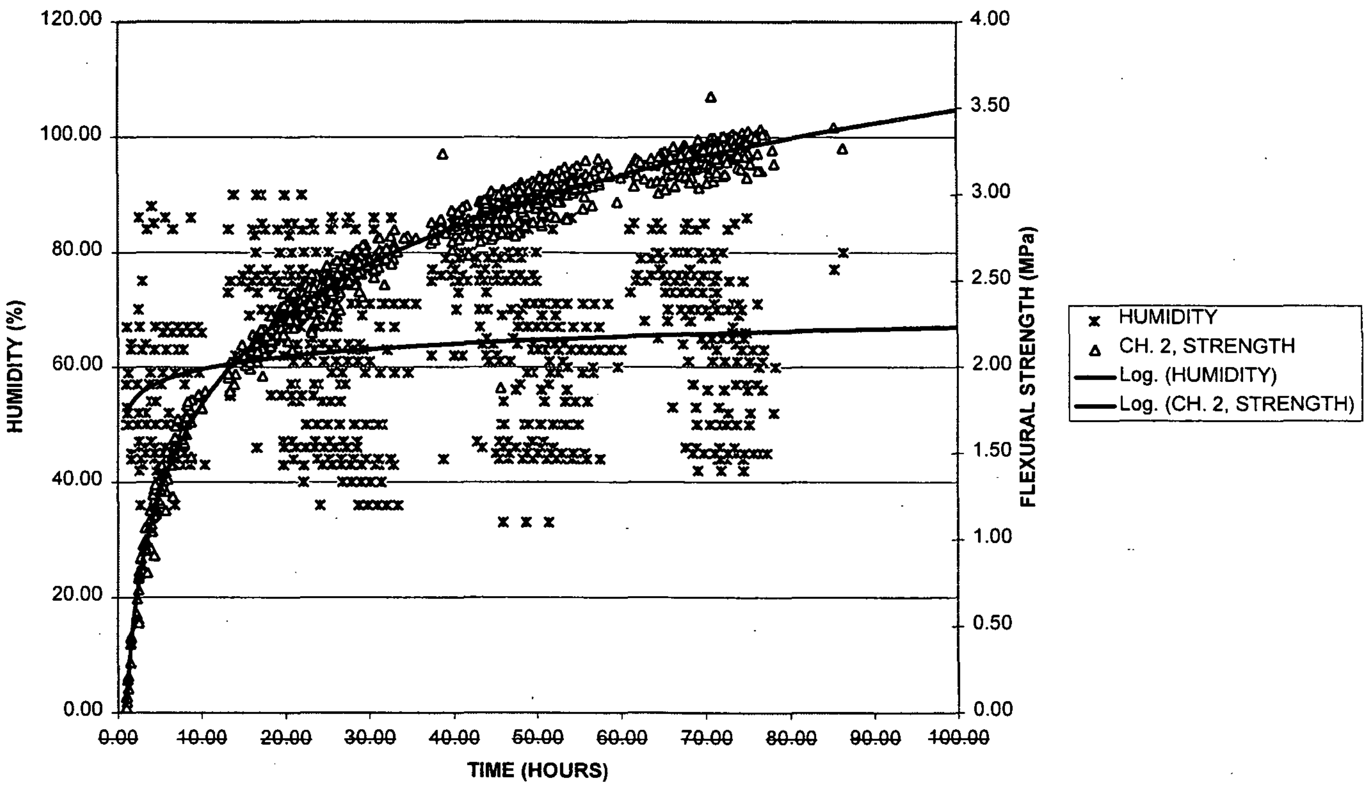


Figure 29, Maturity Strength vs Time vs Humidity (Middepth)

The relationship (curve shape) between the time of curing and the concrete strengths for both the mainline and shoulders is as would be expected for most concrete mixes tested thus far for the Iowa DOT. The points shown on the graphs for each represent the data from all the sites measured by the handheld recording devices. Differences in the curve shape would be expected if changes in the mix materials were made during the project to produce an earlier or later setting mix. If the graphs representing the top, middepth and bottom of the mainline slab, or top and middepth of the shoulders, are superimposed, the impact of the temperature gradient from top to bottom of slab can be identified. In this project the temperature differences between top and bottom did not have a large impact on the final curve. They could have impacted the time of sawing vs time of opening if the contractor has chosen to use the early softcut method of joint development.

The statistical equation for each of these lines is available, but only applicable to these project mix and site conditions. The R-squared values for each of the mainline and shoulder equations exceeded 0.98 when the data was fit with a natural log function equation. Data points that exhibited zeros or incomplete data in terms of temperature and humidity were not included in the analysis.

Relative humidity was also correlated to the strength and cure time relationship in the same manner for both the mainline and shoulder data. A natural log function equation was developed for the top, middepth and bottom of the mainline and top and middepth of the shoulder pavement. The R-squared values of 0.03 for the mainline and 0.04 for the shoulders indicated that the relationship was almost nonexistent. The graphs indicated the large amount of scatter and the difficulty encountered in attempting to find a relationship. This type of data may be very helpful in understanding the reasons for premature or shrinkage cracking in some pavements, but does not apply well to maturity measurements.

Individual graphs of the relationships are available upon request and are stored with the project files.

### Pulse Velocity Results

This project was designed to identify the difference in the pulse velocities measured transversely between the edge of the slab and a point 1 ft. (305 mm) across the slab; between 1 ft. (305 mm) and 2 ft. (610 mm) from the edge of slab; and longitudinally in holes 1 ft. (305 mm) from the edge of the slab and 1 ft. (305 mm) apart. The Pulse velocity measurements were designed to be obtained near the maturity measuring device locations at the edge of the pavement. Pulse velocity was to be measured in a longitudinal direction at locations near the beginning (near the first maturity location) of the day's placement and at locations of approximately 500-ft. (152.4 m) intervals during the day's placement (excluding the end of day maturity location). The first location each day was designed to include a third well placed at right angles to one of those in the longitudinal direction. Measurements were made in both transverse and longitudinal directions at this site to determine the effect of testing location relative to the edge of slab. Several problems were encountered in the use of the pulse velocity equipment. They can be summarized as follows:

1. The equipment developed to install the metal tubing for shaping the test wells in the plastic concrete required the use of electrical power. The work had to be accomplished after the pavement texturing and curing was completed behind the paver. This meant that a portable generator had to be moved by hand between sites or carried on some type of contractor wheel mounted bridge. The lack of shoulder space prevented the use of vehicles for rapid movement of this test equipment. A contractor work bridge was used the first day with some success. The paving speed of over 1 mile per day (1.609 km/day) made movement of this test equipment difficult at best.
2. The test well side wall must be smooth to provide for complete contact with the geophone sensors. This was accomplished with the use of the rectangular metal tubing inserts to form the hole. Thee tubing inserts must be well greased or oiled prior to insertion to allow for ease of removal and retainage of the smooth wall surface.
3. The test well holes must be protected from loss of moisture in the sidewalls to properly represent a valid

test of the concrete strength. This was met to a large degree by the insertion of styrofoam blocks in the test wells for the periods of time between the tests.

4. Pulse velocity measurements were not consistent between holes at a given site and between consecutive times of measurement. We learned that they are difficult for inspection people to understand in terms of electrical control, calibration and achievement of a solid contact on the test well wall. Even with the use of grease on the surface of the geophone prior to testing, errors of large magnitudes were easy to obtain. Changes in temperature, moisture content and contact between the test well wall and the geophone can greatly effect the answer in terms of estimated pavement strength.

The overall problems in manpower requirements for development of the test wells and movement of the equipment; coupled with the difficulties in obtaining consistent information caused the research team to discard this test method after the first day of mainline paving.

### Air Temperature and Humidity Relationships

This portion of the research was aimed at monitoring the air temperatures and relative humidity using selected thermometers and insert devices to examine the relationships between these variables and their impact on the rate of pavement strength gain. The devices were also evaluated as to the effectiveness of their use by field staff. This monitoring was done by ISU Staff at each of the pavement test locations where the hand held temperature measuring devices were used.

It was the intent of the research staff to record air temperature at the initiation of joint sawing vs concrete placement time and maturity values to determine the effect of that timing and development of any visual distresses. On this project the contractor chose to retain the conventional sawing plans and saw in the evenings when the construction was not under way. This type of operation did not provide the type of early opening information that the research team desired and therefore was not recorded.

### *Visual Distress Survey Results*

Visual walking distress surveys were conducted on three separate occasions on this project. The project was first surveyed on November 10, 1995. This consisted of a partial survey conducted by the principal investigator walking from north to south on the north portion (Station 321+75 to Station 353+40) of the project. The survey was halted due to rain and mud from construction equipment on the slab obscuring the surface condition. The principal investigator also conducted a second survey on April 6, 1996. This consisted of a complete survey conducted from north to south of the project length. Greg Mulder, Lisa McDaniel and the principal investigator conducted the third survey on April 5, 1997.

The surveys identified three major types of cracking:

1. Longitudinal cracking in the mainline panels at the outer wheel path and midpanel location.
2. Corner cracks in mainline panels
3. Diagonal cracking in mainline panels
4. Transverse cracking in the shoulder units associated with the joint construction.

Each of the individual distresses can be explained to some degree due to the dates of formation, type of distress, location and the construction practices employed on the project.

1. Transverse cracking. This distress has been noted only in the concrete shoulder sections at the transverse joints. In the southbound shoulder it occurs at some 45 joints in the areas of stations 92+00 to 93+00, 196+00 to 197+00, and 318+00 to 368+00. These sections were paved on days 18, 17 and 16 consecutively of the paving operation. They represent paving of shoulders in a mainline area paved two weeks prior to the shoulder work. Nineteen of the cracks appeared immediately after paving and the remaining 24 were observed the following spring. Each began at the mainline joint and traveled transversely across the shoulder section rather than follows the skewed joint across the shoulder.

   The transverse cracks in the northbound shoulder follow the same location pattern relative to the sawed skewed joint. In this case some 60 shoulder slabs are cracked in the areas of stations 49+00 to 157, 206+00 to

236+00, and 296+00 to 367+00. These areas were paved on days 19 and 26, 22 and 15. Again the data indicates a full two weeks between the mainline and shoulder paving.

The Transverse cracking in the shoulders is attributed to three causes by the researcher:

A. The mainline transverse joints were cracked to the point that movement took place from the paving operation on the shoulder area near the joint construction. Vertical movement in the mainline caused undue stress on the shoulder due to the tied condition.

B. Failure to saw the shoulder joint immediately behind the paver allowed the stresses to build in the joint area due to construction traffic during the curing period. Cracking most likely occurred prior to the sawing of the joint in the shoulder.

C. Due to the widening of the base within one year of the pavement construction and the limited width of embankment outside the shoulder areas, the addition of the shoulder concrete weight causes extra stress on the joint areas and the ties to the mainline.

Much of the shoulder cracking could have been averted by formation of the transverse joint immediately behind the paver while the concrete is still plastic.

The mainline pavement exhibited only minor amounts of longitudinal, diagonal, and corner cracked slabs.

Each of these types of distress was not noted until the 1997 survey or 1.5 years after construction. The corner-cracked slabs were isolated in two slabs located in the southbound lane at stations 343+00 to 344+00, and 224+00 to 225+00. In the northbound lane one corner crack was found between stations 243+00 and 244+00. These cracks are tight and not showing any signs of movement. They appear to be the result of nonuniform settlement from the widening of the subgrade prior to paving.

The four diagonal cracks all occurred in day seven of the paving and are located between stations 30+00 to 31+00 and 71+00 to 72+00 in the northbound lanes. This area is one where the action of the shoulder addition on a relatively new and narrow fill area caused undue stress on the mainline slab. This type of crack is usually the result of nonuniform settlement under the slab. This project experienced heavy rains prior to paving and in the following spring that created large movements of ground water around and under this pavement. This could account for some of the isolated pavement cracks such as this.

The longitudinal cracks are primarily located in the outside wheelpath areas with a small amount being near the midpanel location. Eighteen such cracked slabs were noted in the southbound lane between stations 16+00 to 27+00, 176+00 to 177, and 222+00 to 223+00. Due to their observance at 1.5 years and the specific isolated locations being primarily in the outer wheelpath, they appear to be the result of shifts in the subgrade due to the widening operation. This conclusion is borne out to a greater degree in the northbound lanes were some 58 cracked panels were observed. Forty-nine of those slabs were found in the area between stations 0+00 and 74+00. The remaining cracked slabs were noted between stations 245+00 to 246+00 and 290+00 to 292+00.

This type of cracking could be reduced where additional right of way can be purchased. On this project there were geographical features that prohibited this solution short of major grading work.

The surface distresses noted in the mainline paving do not appear to be the result of any of the research into the use of NDT measurements and reduced strength of concrete at opening to traffic. Those in the shoulders do indicate that the joint construction timing must be reduced to account for movement in the mainline slabs or consider the use of rectangular joints in both the mainline and shoulder areas.

### *Deflection Survey Results*

Roadrater deflection testing was suggested for approximately 35 joint and 35 midslab locations in each direction by Iowa DOT Materials staff upon completion of the paving in the project proposal. The program was designed to provide joint load transfer data at approximately 0.2 mile (0.3 km) increments in both directions of travel. Midslab deflection information was also gathered in the same manner and at the same interval but offset from the joints by 0.005 mile (0.008 km) This data was collected on November 8, 1995, immediately after all paving was completed.

Deflection load transfer is defined as the ratio of the deflection of the unloaded side of the joint to the deflection on the loaded side of the joint. Testing was accomplished by the use of the Iowa Roadrater device. Most pavement evaluation personnel consider load transfer values of 80% or more to be desirable. Values between 50% and 80% indicate potential problems that may develop at the joint in the future. In this project three values of 72% to 78% were noted at spot locations in the northbound lane and one 76% spot location in the southbound lane. Each of these value falls in an acceptable range for pavements that do not contain positive load transfer (dowels) in the transverse joints. They also represent areas where construction of the widening in the subgrade may represent a difference or inconsistency in the subgrade support across the roadway at the test locations.

The Iowa DOT staff also conducted deflection testing at selected midslab locations in each direction. Two estimates can be obtained from this analysis. In one case the Iowa DOT estimates the "k" value for the subgrade support at the site.

The range of values found in this testing was typical for Iowa soils in this area (145 to 225 psi in the northbound direction and 97 to 225 psi in the southbound direction) and reflects some of the inconsistencies in soil support that can be expected with the mix of rock and soils found here and the widening/ reconstruction areas occurring along the roadway.

The estimated effective thickness of the pavement can be obtained from dividing the deflection under the load by a factor of 0.50 as identified by AASHTO as the structural coefficient of sound concrete. It is an estimate of the load carrying capacity of the pavement. In this case the results indicate values in excess of the design/construct depth of 7 inches (180 mm). This is a satisfactory measurement for the time at which it was taken. Construction records indicate that the actual constructed depths did exceed the design depth as a result of contractor decision and the fact that paving was placed on a granular base area. The lack of dowels in the transverse joints may have contributed to increased deflection values and increased structural ratings. In any case this represents a benefit for the county in the load carrying capacity of this pavement.

### *Concrete Core Laboratory Testing*

The proposal included obtaining pavement cores from the completed slab by the Iowa DOT Materials staff and compression testing by the Iowa State University staff to represent 7, 14 and 28 day compressive strengths for each days construction placement of concrete. This portion of the research effort was deleted after discussions between the two agency staffs identified no major relationship of this work to the objectives of the project.

The Southeast Iowa Transportation Center Materials staff, for the purpose of developing a curve to relate time, temperature, strength, and maturity and pulse velocity did compression testing. Those results were illustrated earlier in this report.

### *Equipment Laboratory Testing*

It became evident during the first three days of paving that the level of available personnel to gather the research data in the field was not adequate to meet the needs of the pulse velocity and maturity measurements. Adjustments were made as a result of the forward paving speed to allow for use of the recording maturity meters at the beginning and end of each day. The pulse velocity devices were not used for the reasons stated previously. The hand held thermometers were used to measure maturity at 500-1,000 foot (152.4-304.8 m) intervals. In making these changes, the existing project staff were able to conduct several measurements at each location during a given day regardless of the distance between successive paving locations on the project. The changes also drove the need for the preparation of many additional maturity wire leads and the addition of the metal plugs on the wire lead end for insertion into the recording devices. It was not possible on some days to prepare the wire lead connections in a timely manner and thus the wires were directly inserted (bare) into the thermometer connections. A test was needed to measure the impact of that decision on the accuracy of the data collected.

In December of 1995, four flexural test beams were constructed in the Civil Engineering Structures laboratory at ISU. Thermocouple wire leads were installed at locations 3, 6 and 9 inches (75, 150, and 225 mm) from each end of the beams. The first thermocouple on each end was connected with the aid of the two prong connectors to a recording maturity meter. The same type of connectors was placed on the second set of lead wires at each end of the beams. The third thermocouple at each end of the four beams was stripped of insulation for approximately 1 inch (25 mm). The recording devices were used to monitor the maturity gain at each end of the beam for some 71 hours. The hand held Thermometers were used to measure the temperature in degree Celsius at 2-4 hour increments during the daytime hours only. These measurements were made by both handheld devices at the wires with connectors and those without connectors. The measurements from each of the devices and the combinations of connector/no connector wires were analyzed for variance. No variance was found to be significant between the handheld devices, the handheld and recording devices and the use or deletion of the connectors from the thermocouple leads.

### ***NDT Instructional Memorandum***

The development of an instructional memorandum (I.M.) for the use of the maturity, pulse velocity or other identified NDT methods to determine the rate concrete pavement strength gain was an objective of this research work. The memorandum was directed to identify testing equipment that could be practically deployed by highway agency personnel or contractor forces. It was to include but not be limited to the use of pulse velocity or maturity devices and thermometers of various types. The I.M. would describe the equipment to be used, materials required, frequency of testing, and the methods to be employed in the laboratory or field to establish the initial relationships and the field construction verification information.

The Iowa DOT staff saw the benefits in the methodology during the Lee County research project data collection phase. In consultation with the ISU research team, Iowa DOT field staff and contractor assistance, I.M.-383 was developed and implemented on a limited basis. Data was collected from each of the Transportation Centers on a variety of projects and used to revise the I.M.-383.

Based on that I.M.-383 input, the research team sought comments from the same field staff on how the next revision of the I.M.-383 should be developed. The following comments are the result of that survey. They are made in response to IM-383 dated May 2, 1997.

1. The initial maturity curve should be developed at the project site using the same materials that are used in the paving mix. If at any time during the project <u>any</u> of the dry materials, water or additives are changed by the contractor or contracting authority, a new or

validation curve should be developed from the new mix being sent to the pavement construction site.

2. It is important to develop the maturity curve at the project site to most closely represent the material and climatic conditions at the time and place of construction. This will provide the best relationship for the particular site, time of year and material being sent to the paving site.
3. Twelve flexural test beams should be made for the development of the maturity curve. This will allow for the development of four points with up to three beams being tested for each point.
4. A factor of safety could be built into the maturity curve development process with the use of concrete that was produced with air content and slump near the upper specification limits.
5. The research team suggests that the use of the random truck sample for the original curve development and the implementation of the validation curve process. The validation test provides a check on changes or irregularities in the construction process and provides a better form of protection for the contractor and contracting authority.
6. Hot cement may cause more rapid strength gain in the field placed concrete. It is suggested that the curve be developed from cement that is not exhibiting this

trait to represent the average cement being used. The result of the hot cement will reduce the time required to meet the maturity strength desired.

7. Consider the use of compressive cylinders vs flexural test beams for the curve development. The current philosophy of the Iowa DOT and the research team is that the mode of pavement failure has been flexural rather than compression failures. No change is recommended at this time.
8. Does the wet sand cure of the flexural test beams replicate the cure being experienced by the pavement under the white-sprayed cure method? The data gathered at various locations on this project indicates that the relationship of temperatures achieved in both situations is similar in magnitude.
9. The general portion of the I.M. indicates that the contractor and the agency shall jointly develop a plan for performing the maturity testing. Current general specification changes being made in Iowa, provide for more control of the process by the contractor and will require changes in this language. The contractor should be charged with developing the plan and curve. The highway agency should only cooperate, assist, review and approve or reject the contractor recommended plan.

## SUMMARY AND CONCLUSIONS

This research effort was designed to provide Lee County, Iowa DOT and other governmental units with information on possible NDT ways to monitor the rate of concrete strength gain for determination of traffic opening times under field conditions. The research resulted in the following conclusions relative the selection of NDT equipment, methods of data collection and use of the data for construction project traffic control decisions.

1. Information DataBase Development
   a. The project provided a large database of maturity data for mainline and shoulder construction direction.
   b. Data from multiple Iowa Transportation Centers and multiple types of paving or repair supplemented the development of the Instructional Memorandum.
   c. Project data was limited by the lack of fluctuations in temperatures during construction.
   d. Project data did identify the importance of curing methods and the rapid gain in concrete flexural strength during the first 24-48 hours after placement. Supplemental methods of retaining the heat in the slab may be required during Spring and Fall paving to achieve desired rates of strength gain.
2. NDT Equipment selection:

a. Pulse Velocity devices are not recommended for measurement of pavement strength gain due to equipment/space needs, limitations in field measurement operation and operator training requirements.

b. Recording maturity meters should be used for research purposes where long periods of recording are required or where personnel are scarce. They are susceptible to water damage and theft.

c. Handheld digital thermometers were found to be very successful in the monitoring of many maturity sites by one person. They can be connected adequately to the thermocouple wires with a two-prong connector or the insertion of the two bare, clean and dry thermocouple wires into the gage connection point.

3. Maturity Depth and Location Measurements:

a. Location and depth of the thermocouple wire is dependent on the use of the data. The ideal lateral location for the wire is at least one foot (310 mm) from the edge of the pavement.

b. Decisions regarding joint sawing timing should be based on data from a thermocouple placed within one inch (25 mm) of the concrete surface.

c. Measurements taken at the middepth of the concrete are useful in the determination of the average strength of the slab and should be used in the determination of pavement opening times.

d. Temperature data taken at variable depths in the pavement or subgrade are helpful in understanding the temperature gradients through the depth of the slab.

e. Thermocouples can easily be mounted on wood dowels and inserted to the required depth in the slab. They may be left in the slab after measurements have been completed.

f. Longitudinally, the thermocouples should be inserted at intervals of 500 to 1,000 ft. (152.4 to 305 m's') to account for changes in climatic conditions during the day and to provide for accurate estimation of joint formation timing.

4. Pavement Visual Distress Relationships.

   a. Transverse cracking in shoulders was found where shoulder joints were not formed in a timely manner.

   b. Minimal longitudinal and corner/diagonal cracking was observed on the project two years after construction in the outer wheel path locations in areas of subgrade widening. Irregularities in the subgrade due to construction were identified as the primary cause of the cracks.

5. Maturity Instructional Memorandum Development.

   a. Instructional Memorandum #383, dated October 28, 1997 includes many of the comments and suggestions by those using the equipment in the field.

b. The recommendations regarding the use of the validation tests and the target opening strength time temperature factors represent results noted in this research and are recommended for future use.

Project engineers now have more flexibility in the development of project construction specifications to meet both public traffic demands and long term pavement performance.

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